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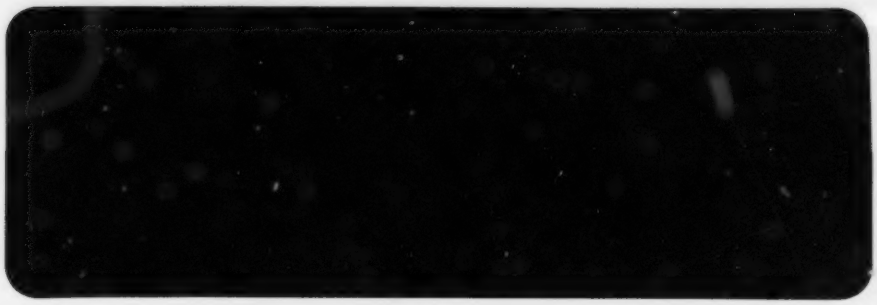

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LONG-TERM MONITORING AND DATABASE DEVELOPMENT FOR APPLIED ANAEROBIC DIGESTION TECHNOLOGY IN CANADA

PREPARED FOR:

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PREFACE

Anaerobic digestion is a biological waste treatment process in which organic matter is decomposed in the absence of oxygen. It is used in Canada to treat a wide variety of industrial and agricultural wastes. Many digestion system design configurations are available and well documented but specific operational information dealing with individual systems across the country is often difficult to obtain.

In 1985, Energy, Mines and Resources Canada recognized the need to organize this information into an easily accessible format and the Canadian Applied Anaerobic Digestion Database (CAADD) was developed. Over the past six years, the database has been continuously updated with specific Canadian operational data as well as with general information dealing with advancements made in anaerobic digestion technology.

This report provides a brief overview of the activities relating to the CAADD from 1985 to 1991.

ABSTRACT

The overall objectives of this project were: to develop a computerized database to contain process design information from Canadian anaerobic digestion facilities operating on agricultural and industrial wastes, to develop a digester process monitoring and data collection program to update the database with operational data, and to develop a computer conferencing system for information exchange. These objectives were met with the development of the Canadian Applied Anaerobic Digestion Database (CAADD) and the Anaerobic Digestion System Monitoring Program.

The CAADD has become an excellent source of reference material on the current and historical development of anaerobic digestion technology in Canada.

EXECUTIVE SUMMARY

Three papers were prepared emphasizing biogas utilization and energy recovery from anaerobic decomposition of solid waste in municipal landfills and the treatment of wastewaters generated in the pulp and paper industry and food processing industry. The papers are designed to stand alone and be used for general information for managers and engineers interested in utilizing energy recovered from anaerobic technology applied to high strength waste streams and landfilling operations.

HISTORY OF CANADIAN APPLIED ANAEROBIC DIGESTION DATABASE

The general technology of anaerobic digestion is well known and has been applied for many years to treat the waste sludge generated in municipal wastewater treatment plants. Stimulated by national goals of energy self-sufficiency and by concerns with environmental protection, anaerobic digestion technology has more recently been applied to the treatment of agricultural and industrial wastewaters as well.

In the past, information concerning the design and operation of Canadian agricultural and industrial anaerobic digestion systems was difficult to obtain. Therefore, in 1985/86, Energy, Mines and Resources Canada contracted the development of the Canadian Applied Anaerobic Digestion Database (CAADD) with the purpose of compiling this information.

An inventory of Canadian agricultural and industrial anaerobic digestion systems was completed by contacting federal and provincial government officials, universities, engineering firms and individuals involved in anaerobic digestion technology. An extensive literature review of project reports, presentations, journals and other publications was conducted.

Questionnaires were distributed to collect design and operating data at each system. The questionnaires were partially completed with information available from the literature prior to being forwarded to system operators for verification and/or completion. A summary of the anaerobic digestion systems design and operational information was published in the form of the 1987 annual report.

A digester monitoring program, designed to obtain digester operational information, was developed. The program involved collecting monthly samples of digester influent, effluent and biogas as well as obtaining operator comments from several of the operating digestion systems. The analytical data and operator comments were summarized in a number of offline reports.

Due to increased growth of anaerobic systems in Canada and the practical operating information available from other sources, the digester monitoring program was discontinued in 1988.

The current activities involve the preparation of three overview papers entitled:

- Volume I - Overview of Landfill Gas Utilization and Energy Recovery
- Volume II - Overview of Biogas Utilization and Energy Recovery in the Pulp and Paper Industry
- Volume III - Overview of Biogas Utilization and Energy Recovery in the Food Processing Industry

Copies of the papers are included as Appendix A.

The papers are designed to encourage managers and engineers to apply anaerobic technology, biogas utilization and energy recovery systems to industrial wastewater treatment and landfill gas recovery projects.

SUMMARY

The Canadian Applied Anaerobic Digestion Database was developed to monitor full-scale anaerobic digestion systems operating on agricultural and industrial wastes in Canada and to provide a forum for information exchange.

The Canadian Applied Anaerobic Digestion Database provided an effective method of bringing groups of people together to exchange information on developments in the field of applied anaerobic digestion technology. It is an excellent source of reference material on the current and historical development of anaerobic technology in Canada. The database and technical papers developed during this project has and will assist Energy, Mines and Resources in increasing the use of renewable energy resources in Canada through technology development and technology transfer activities.

The number of installations of anaerobic wastewater treatment systems with biogas utilization and energy recovery systems continues to grow as the operating experience bears out the applicability of anaerobic treatment to a wide variety of wastes.

SOMMAIRE

Trois rapports ont été rédigés sur l'utilisation des biogaz et la récupération de l'énergie provenant de la décomposition anaérobie de déchets solides dans les décharges municipales, et provenant aussi du traitement des eaux usées produites par l'industrie des pâtes et papiers et l'industrie de la transformation des aliments. Ces trois rapports indépendants les uns des autres contiennent de l'information générale à l'usage des gestionnaires et des ingénieurs qui s'intéressent à l'utilisation de l'énergie produite par l'application de la technologie de la digestion anaérobie au traitement des eaux usées et des déchets.

DÉVELOPPEMENT DE LA BASE DE DONNÉES CANADIENNE SUR LA DIGESTION ANAÉROBIE ET SES APPLICATIONS

Globalement, la technologie de la digestion anaérobie est bien connue; on l'emploie depuis plusieurs années pour traiter les boues produites dans les usines municipales de traitement des eaux usées. Depuis plus récemment, sous l'impulsion des programmes nationaux d'autosuffisance énergétique et de protection de l'environnement, on s'en sert également pour traiter les eaux usées dans les secteurs agricole et industriel.

Par le passé, il était difficile d'obtenir de l'information sur la conception et le fonctionnement des systèmes de digestion anaérobie en usage dans les secteurs agricole et industriel canadiens. Aussi, en 1985-1986, le ministère de l'Énergie, des Mines et des Ressources a-t-il fait établir par contrat la Base de données canadienne sur la digestion anaérobie et ses applications, afin de rassembler toute cette information.

On a dressé un inventaire des systèmes de digestion anaérobie utilisés au Canada dans les secteurs agricole et industriel, en se mettant en rapport avec des organismes fédéraux et provinciaux, des universités, des cabinets d'ingénieurs et des paticuliers qui s'intéressent à cette technologie. Parallèlement, on a procédé à un dépouillement systématique des rapports de projets, des exposés, des journaux et des autres publications traitant de la question.

On a distribué des questionnaires, afin de recueillir des renseignements sur la conception et le fonctionnement de chaque système. Après y avoir inscrit l'information trouvée dans la littérature, on les a envoyés à des opérateurs de systèmes pour vérifier et compléter les renseignements. Un résumé de l'information disponible sur la conception et le fonctionnement des systèmes de digestion anaérobie a été publié dans le rapport annuel de 1987.

On a aussi mis sur pied un programme de surveillance visant à obtenir de l'information sur le fonctionnement des digesteurs. Il s'agissait de prélever chaque mois des échantillons des déchets, des boues et des gaz, et d'obtenir les opinions des opérateurs sur plusieurs des systèmes de digestion en exploitation. Les données de l'analyse et les commentaires des opérateurs ont été résumés dans un certain nombre de rapports spéciaux.

APPENDIX A

VOLUME I

OVERVIEW OF LANDFILL GAS UTILIZATION AND ENERGY RECOVERY

ABSTRACT

Landfill gas generated from anaerobic decomposition processes within landfills provides a potential alternative energy source. Research and development of viable alternative energy sources together with efforts to mitigate environmental impacts of landfills have resulted in the development of landfill gas utilization technology. This report provides an overview of landfill gas utilization technology and discusses current trends in the industry.

Landfill gas production is discussed and production rates are presented for low, average and high production conditions. Landfill gas collection efficiencies are also reported.

Landfill gas extraction systems provide effective means for mitigating environmental impacts and are essential components of utilization projects. The dual function of extraction systems and its bearing on the economic evaluation of landfill gas utilization schemes are discussed.

Landfill gas utilization technology can be broken down into three utilization categories: medium BTU fuel, high BTU fuel and electrical power generation. The components of each technology are discussed including treatment processes, transmission and energy conversion. Economic and regulatory considerations are also presented and preliminary relationships between landfill capacity and utilization potential are constructed.

Several operational landfill gas utilization systems located in Canada are discussed. Pertinent features relating to each system are presented in a summary table. A similar table is provided for a selection of operational landfill gas utilization systems located in the United States.

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Section 1
LANDFILL GAS UTILIZATION OVERVIEW

INTRODUCTION

Landfill gas generation, resulting from anaerobic decomposition processes within landfills, provides a potential alternative energy source. Landfill gas is composed primarily of methane and carbon dioxide, typically having a heating value ranging from 14.9 to 20.5 MJ/m^3 (400 to 550 BTU/scf), approximately half that of natural gas.

Numerous landfill gas utilization projects have been implemented in North America (primarily in the U.S.) and Europe. These projects include the sale of medium BTU gas to local industries as fuel for boilers, furnaces, and cement-brick kilns; upgrading of landfill gas to natural gas pipeline quality; and generation of electricity using reciprocating engines or turbines.

In the U.S.A. it is estimated that approximately 150 million tonnes of municipal solid waste are landfilled each year (Wolfe and Maxwell, 1990), which represents approximately 1,000 PJ (175 million barrels of oil equivalent) buried each year. It has been estimated that approximately 9 PJ were recovered in 1987 through landfill gas utilization projects throughout the U.S. In 1987, a total of 50 landfill gas utilization projects were in operation in the U.S. and an additional 44 projects were scheduled for operation (Klass, 1990).

According to Statistics Canada, 16 million tonnes of municipal solid waste were produced in Canada in 1986 of which 14.6 million tonnes were landfilled. This represents a recoverable energy potential of 100 PJ per year. In 1986 the total energy consumption in Canada has been estimated to be almost 7,000 PJ per year (Dent and Krol, 1988).

To date, virtually none of the energy in Canadian landfills has been harnessed. Landfill gas utilization schemes are generally deemed uneconomical due to the small size of most landfills (less than 1 to 2 million tonnes) and few incentives. In contrast, in the U.S. the Public Utility Regulatory Policies Act of 1978 (PURPA) provides benefits to small power producers, creating a more favourable economic climate for the implementation of landfill gas utilization projects (Klass, 1990). However, if the present trend towards larger engineered sites continues, along with requirements for greater environmental control, the Canadian economic climate for the implementation of landfill gas utilization projects will improve.

LANDFILL GAS PRODUCTION

The production of landfill gas is caused by anaerobic decomposition of the organic fraction of municipal refuse. When refuse is initially landfilled, biological breakdown occurs by aerobic processes due to the presence of oxygen. As free oxygen disappears, aerobic organisms are replaced by anaerobic organisms which break down additional organic materials into methane and carbon dioxide. Typically, the shift from aerobic to anaerobic decomposition occurs over a period of one to two years (Ward, 1988). The methane content of the generated gas generally varies from 40 to 60 percent. The exact chemical make-up of the landfill gas depends on several parameters including the organic content of the refuse, the age of the landfill, the rate of decomposition, the temperature and moisture content. The heating value of the landfill gas typically ranges from 14.9 to 20.5 MJ/m^3 (400 to 550 BTU/scf).

Researchers have calculated the theoretical maximum landfill gas production to range from 187-375 m^3/tonne (3 to 6 scf/lb) of refuse (Wolfe and Maxwell, 1990), while in practice the volume recovered over a 6 to 10 year period generally ranges from 11 to 94 m^3/tonne (0.18 to 1.50 scf/lb) (Forseth, 1982). Experience gained by Waste Management of North America indicates that while landfill gas production rates may range from 3 to 14 m^3/tonne/year (0.05 to 0.23 scf/lb/year), the average production rate is 6.9 m^3/tonne/year (0.11 scf/lb/year) (Wolfe and Maxwell, 1990). Landfill gas recovery rates typically vary from 75 to 85 percent of production rates for medium BTU and electrical power generation projects, while for high BTU projects recovery is typically less than 75 percent.

The time period over which the majority of the landfill gas is generated from a given cell of refuse varies depending on site conditions. Waste Management of North America has adopted a 10 to 15 year planning horizon for gas generation, whereby an initial annual gas generation rate is assumed (to be confirmed/altered through field testing) with a constant rate of decline in gas production for each subsequent year (Wolfe and Maxwell, 1990). The decline in gas production results from a decrease in available digestible material. The formula used to determine the annual rate of decline in gas production is described below.

$$\text{Annual Rate of Decline in Gas Production} = \frac{\text{Initial Gas Production Rate}}{\text{Total Gas Production}} \times 100\%$$

In the case that the initial gas production rate is assumed to be 6.9 m^3/tonne/year (0.11 scf/lb/year) and the total gas production is 281 m^3/tonne (4.5 scf/lb), the annual rate of decline in gas production is 2.46 percent.

To obtain an initial estimate of landfill gas production rates at a landfill, the above equation can be used to analyze three scenarios: low, average and high gas production. These scenarios reflect poor, average and favourable conditions for which assumed

parameter values are given in Table 1.1. The first year of gas production for a cell of refuse is assumed to commence two years following placement of the refuse.

Table 1.1
Landfill Gas Production Estimates

Parameter	Scenario		
	Low Production	Average Production	High Production
Initial Gas Production Rate (m^3/tonne/year)	3	6.9	12.5
Total Gas Production (m^3/tonne)	281	281	281
Annual Rate of Decline (%)	1.11	2.46	4.45
Planning Horizon (years)	20	15	10

In the case that initial estimates indicate landfill gas utilization may be economically feasible, or that environmental control will be required, more accurate estimates of landfill gas production rates can be achieved through field testing. Field testing can generally provide estimates of gas production within ±20 percent of the actual production rates and may cost in the order of $120,000 ($100,000 U.S.) to conduct (Wolfe and Maxwell, 1990).

LANDFILL GAS EXTRACTION TECHNOLOGY

Landfill gas extraction systems are installed at sites for the purpose of providing environmental control and/or recovery of landfill gas for utilization.

Environmental control systems are implemented to prevent or minimize the potential for migration of landfill gas. More recent concern has focused on landfill gases contributing to the greenhouse effect through venting to the atmosphere. Landfill gas is primarily composed of methane (40 to 60 percent by volume) and carbon dioxide (60 to 40 percent by volume). Due to the combustible nature of methane, landfill gas poses a potential explosive hazard.

The potential for off site migration and entry of landfill gas into building structures varies, depending on site conditions, proximity of buildings and presence of trenches or conduits that can potentially conduct the gas several kilometres.

Environmental control can be provided using a passive venting system such as a perimeter trench filled with coarse aggregate. As landfill gas migrates, it is intercepted

by the perimeter trench and vented. Alternatively, an active landfill gas extraction system may be installed consisting of vertical wells or horizontal trenches connected by piping to a blower. The extracted gas is flared. An active system provides a higher degree of environmental control than a passive system.

A landfill gas extraction system as a component of a landfill gas utilization project will differ in design from an environmental control system. An environmental control system requires that gas be extracted near the landfill perimeter, and in some cases immediately below the landfill cover, which creates a higher potential for air ingress. This gas has a relatively low heating value generally not suitable for utilization and requires separate flaring. Landfill gas extraction for utilization purposes will extract gas from the centre of the landfill where the gas is of a higher quality (Zack and Minott, 1990).

A landfill gas extraction system for both commercial purposes and environmental control must incorporate design aspects suitable for both purposes. A rule of thumb for the cost split of a commercial system incorporating environmental control is 40 percent control and 60 percent commercial (Wolfe and Maxwell, 1990). Only the 60 percent should be charged to a commercial project in determining the economic viability of the project.

As the requirements of environmental control become more stringent, the economic viability of landfill gas utilization increases. U.S. federal regulations may require environmental control systems at landfills with total design capacities of at least one million tonnes (Zack and Minott, 1990). A generally accepted rule of thumb in the U.S. is that a minimum design capacity of 2,000,000 tonnes is required to implement an economically viable landfill gas utilization scheme.

To maximize landfill gas recovery for utilization, progressive installation of gas wells can be planned. As sections of a landfill are completed and final cover placed, extraction wells can be installed. The radius of influence of the extraction wells is typically about 50 m, and can be determined from pumping tests. Alternatively, horizontal trenches can be installed and gas extraction commenced prior to placement of final cover. While trenches generally provide more efficient gas extraction from shallow sites, rising leachate levels may completely block lower trenches located in deeper landfills (Fletcher, 1989).

At the preliminary planning stage, the capital cost of a commercial landfill gas extraction system can be assumed to be approximately $400,000 per million tonnes ($300,000 U.S. per million tons) in place with a maintenance cost of $18,000 ($15,000. U.S.) per year (Wolfe and Maxwell, 1990). The gas recovery rate generally varies from 75 to 85 percent of the landfill gas production rate for medium BTU and electrical power generation projects, while for high BTU projects the recovery rate is typically less than 75 percent since a higher quality gas is required.

Section 2
LANDFILL GAS UTILIZATION TECHNOLOGY

Gas generated from landfills typically has a heating value of 14.9 to 20.5 MJ/m^3 (400 to 550 BTU/scf), approximately half the heating value of natural gas. As a result, landfill gas provides a potential alternative energy source that can be utilized in various ways, depending on the achievable rate of gas recovery and the market conditions for alternative energy sources.

Landfill gas utilization technology may be broken down into three utilization categories: medium BTU fuel, high BTU fuel and electrical power generation.

MEDIUM BTU GAS TECHNOLOGY

Medium BTU gas technology essentially consists of pretreatment and transmission of landfill gas for direct sale to neighbouring industries. Such industries may include cement kilns, steel mills, petroleum and petrochemical plants, pulp and paper mills and greenhouses, at which the landfill gas may be utilized as a fuel for boilers, furnaces, kilns and gas engines. A schematic illustrating the components of a medium BTU landfill gas utilization system is provided in Figure 2-1.

Landfill gas is principally composed of methane and carbon dioxide with trace levels of nitrogen, oxygen, hydrogen, hydrogen sulfide, hydrocarbons, chlorides and other trace compounds. Table 2.1 shows the typical landfill gas composition by percent (adapted from Hernandez, 1990). In addition, raw landfill gas has a high water content of typically 56 g/m^3 (3500 lbs/MMscf) as compared to pipeline quality natural gas of less than 0.11 g/m^3 (7 lbs/MMscf).

The high moisture content, coupled with the presence of carbon dioxide and other undesirable compounds can result in the formation of carbonic acid and hydrochloric and hydrofluoric acids, creating a very corrosive environment for gas transmission and utilization equipment. To reduce damage of equipment, pretreatment of the landfill gas is required.

PRETREATMENT

Pretreatment of landfill gas prior to use as a medium BTU fuel may consist of two stages:

1) removal of water
2) removal of toxins

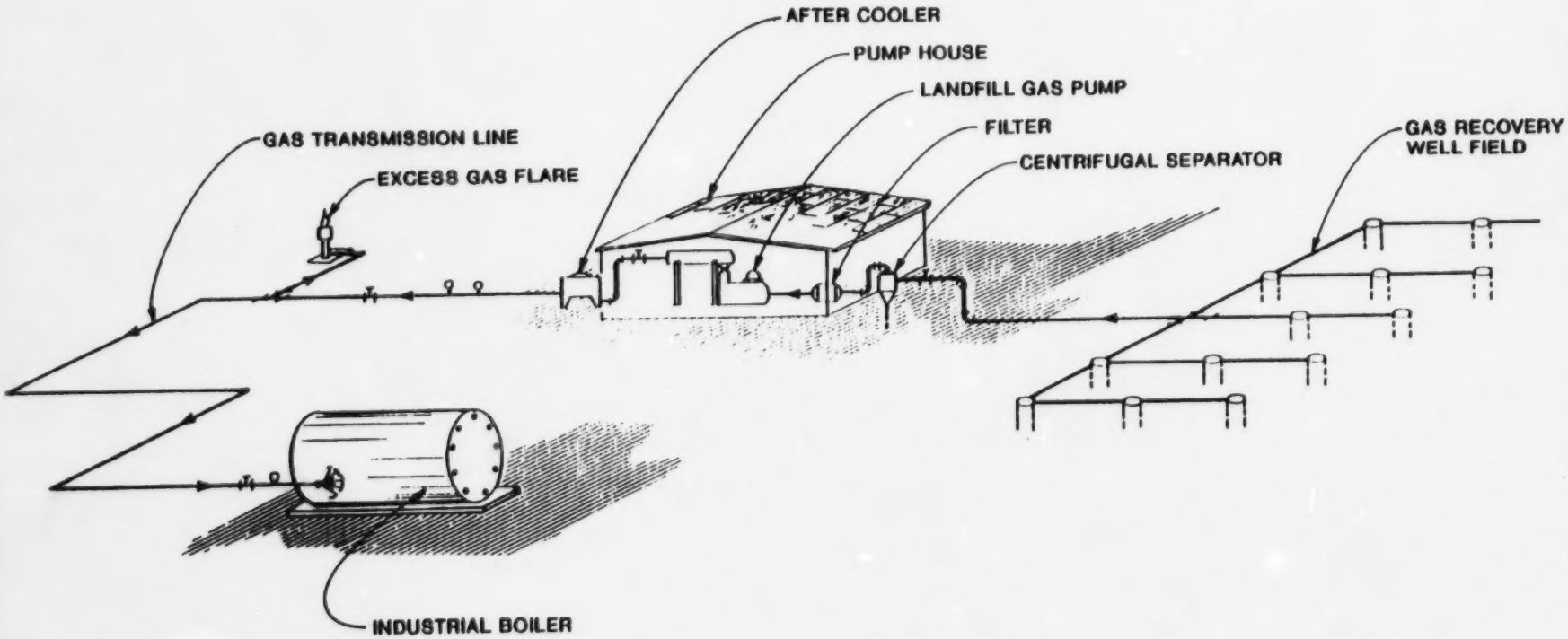

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FIGURE 2.1:
SCHEMATIC OF MEDIUM BTU LANDFILL GAS UTILIZATION SYSTEM
(Adapted from Environment Canada, 1987)

Generally, the quality of medium BTU gas produced increases with sophistication of the treatment process. The expenses, however, escalate rapidly (Environment Canada, 1981). As a result, the level of treatment provided is largely driven by gas recovery rates, user proximity and market conditions.

Table 2.1
Typical Landfill Gas Composition and Characteristics

Components	Component Percent (dry volume basis)
Methane	47.5
Carbon Dioxide	47.0
Nitrogen	3.7
Oxygen	0.8
Paraffin Hydrocarbons	0.1
Aromatic and Cyclic Hydrocarbons	0.2
Hydrogen	0.1
Hydrogen Sulfide	0.01
Carbon Monoxide	0.1
Trace Compounds*	0.5
Temperature at Source	41°C
Heating Value	17.7 MJ/m^3 (475 BTU/scf)
Moisture Content	Saturated

*Trace compounds include sulfur dioxide, benzene, toluene, methylene chloride, perchloroethylene, and carbonyl sulfide in concentrations up to 50 ppm.
Adapted from Hernandez, 1990.

Removal of Water

Several methods exist to remove water or condensate from the landfill gas. These methods include knock-out drums, moisture traps, chilling and absorption methods.

The use of knock-out drums is perhaps the simplest method. Knock-out drums may be employed as a primary removal method or as a preliminary step in the pretreatment process.

Knock-out drums are connected to the collection line so that gas flows into the drum, causing entrained liquids to collect in the drums. The gas then exits the top of the drum, to be transmitted for utilization or further treatment. In many cases, this level of treatment is inadequate.

A variation on the knock-out drum is a centrifugal separator. The drum or tank is designed to swirl or centrifuge the landfill gas in order to plate out water on the sides

of the tank (Environment Canada, 1987). This provides a higher water removal efficiency than simple knock-out drums.

A series of moisture traps along sloped pipes provide an additional method for removing condensate present in the gas collection pipeline. As gas flows up slope, condensate drains down slope and collects in moisture traps where it is allowed to re-enter the landfill. Due to the toxic nature of the condensate, it may be difficult obtaining approval to dispose of this liquid waste into the landfill without some treatment, although the liquid originated from the landfill. In some cases, the condensate is mixed with other site effluents such as leachate and discharged to the sanitary sewer.

A chiller or after cooler, placed in sequence with a compressor, chills the compressed gas, causing further condensing of entrained liquids. This removal process, in conjunction with knock-out drums and/or moisture traps comprises the pretreatment method employed at many medium BTU gas utilization projects (Love, 1990).

To attain a higher water removal efficiency, as well as removal of toxins from the recovered landfill gas, an absorption treatment method may be employed. One of the most widely accepted absorption methods is the Selexol process (Love, 1990), used for both medium and high BTU gas utilization projects. Another successful absorption method is the ethylene glycol (EG)/refrigeration process. These processes are discussed further in the following section.

Removal of Toxins

Additional treatment may be provided for the removal of toxins from the recovered landfill gas. This is generally done only for large medium BTU gas utilization projects. The Selexol process and EG/refrigeration process are common methods employed to remove toxins in addition to the removal of water. Other methods of treatment, including adsorption and semi-permeable membrane (osmosis), are discussed under sub-section heading High BTU Gas Technology.

The Selexol process utilizes an organic solvent to absorb both moisture and other toxins present in landfill gas. The raw gas first passes through a liquid/gas separator (i.e. knock-out drum), is compressed and then flows through an iron sponge unit to remove hydrogen sulfide, if present. Next, the gas flows to the absorber, or may first be chilled. The Selexol solvent absorbs H_2O and trace contaminants. The cleaned landfill gas, having a heating value in the range of 18.6 MJ/m^3 (500 BTU/scf), exits the top of the adsorber, ready for sale. The rich Selexol solvent from the bottom of the absorber is reheated and flows through a stripper column prior to returning to the top of the absorber. The spent stripping gas is flared (Hernandez, 1990).

The relative solubilities of gases in Selexol solvent are presented in Table 2.2 (adapted from Hernandez, 1990). Although the table shows carbon dioxide to have a solubility of 15 times greater than methane, carbon dioxide absorption is usually minimal for a

first pass of landfill gas through the absorber. This is due to the presence of more highly soluble substances. For this reason high BTU gas treatment requires a second absorber to achieve required carbon dioxide removal.

Table 2.2
Relative Solubility of Gases in Selexol Solvent

Compound	Solubility Ratio
H_2 (least soluble)	0.1
N_2	1
CH_4	1
CO_2	15
H_2S	134
CH_3SH	340
Vinyl Chloride	400
SO_2	1400
Benzene	3800
Methylene Chloride	5000
Trichloroethylene	5000
H_2O (most soluble)	11000

Adapted from Hernandez, 1990

Landfill gas recovery rates for existing medium BTU gas utilization projects in the U.S., employing the Selexol process, range from approximately 1.27 to 2.36 m^3/s (2,700 cfm to 5,000 cfm), which is representative of landfills ranging in size from 8 to 15 million tonnes assuming a unit landfill gas recovery rate of 5.0 m^3/tonne/year (0.08 scf/lb/year) (Forseth, 1982).

The EG/refrigeration process effectively removes water and toxins such as chlorinated hydrocarbons. Landfill gas is first cooled to temperatures below -23°C to condense and remove much of the water from the gas. The gas then contacts the EG solvent, which absorbs additional moisture as well as other toxins. Implementation of this process for a medium BTU gas utilization project would require substantial landfill gas recovery rates for it to be potentially economical.

Another absorption method is the Rectisol process, which uses methanol and operates similar to the Selexol process. Although low temperatures (-60°C) are required to achieve the highest absorption efficiency (Love, 1990), studies have shown that the methanol wash process is economically attractive to provide initial pretreatment for the removal of contaminants at ambient pressure and temperature prior to gas compression (Keller and Walsh, 1988). This has the advantage of improving compressor performance.

TRANSMISSION

Transmission of pretreated landfill gas to a local industry utilizing the gas is achieved via a pipeline of PVC or HDPE construction. Steel pipe is not suitable due to its inferior corrosion resistance (Held and Woodfield, 1989). The proximity of the user governs the required length of transmission line which in turn largely governs transmission cost. Transmission cost is a primary consideration in establishing the feasibility of medium BTU gas utilization.

ENERGY CONVERSION

Common utilization modes for medium BTU gas include the use of the gas as a fuel for boilers, furnaces, kilns and gas engines. Often equipment modifications will be required where landfill gas displaces natural gas. As an example, due to the lower heating value of medium BTU gas compared to natural gas, a boiler fuel inlet must be modified to permit a higher fuel gas flowrate to maintain a similar steam generation rate achieved using natural gas.

HIGH BTU GAS TECHNOLOGY

High BTU gas technology can be described as a technology that provides adequate treatment to upgrade landfill gas to natural gas pipeline quality to be assimilated into the natural gas pipeline network. Bulk quantity removal of carbon dioxide is required to achieve a heating value of approximately 37.3 MJ/m^3 (1000 BTU/scf). In addition, water content must be reduced from approximately 56 g/m^3 (3,500 lbs per MMscf) representative of raw landfill gas to 0.11 m/m^3 (7 lbs per MMscf) specified for pipeline quality and toxins must be removed (Hernandez, 1990).

TREATMENT

Production of high BTU landfill gas requires the following stages of treatment:

1) removal of water
2) removal of toxins
3) removal of bulk quantity carbon dioxide

Removal of Water

The water removal efficiency required to achieve natural gas pipeline standards precludes the sole use of simpler water removal methods such as knock-out drums and the chilling process. Two methods that do provide adequate removal include adsorption and absorption methods. However, adsorption methods are generally too expensive for landfill gas treatment applications (Love, 1990).

Various absorption methods have been developed, utilizing organic solvents such as ethylene glycol (EG) and Selexol in conjunction with refrigeration which condenses saturated water in the landfill gas prior to gas contact with the solvent. The high solubility of water in these solvents make these absorption methods effective for water removal.

Removal of Toxins and Carbon Dioxide

To achieve natural gas pipeline specifications, removal of toxins present in raw landfill gas is required. Table 2.1 indicates some of the toxins typically found in landfill gas. Since methods effective for the removal of toxins are also used in bulk quantity removal of carbon dioxide, the two stages of treatment are discussed together.

Several methods have been developed for the removal of carbon dioxide and other toxins (Love, 1990), and include:

1) adsorption
2) semi-permeable membranes
3) absorption

An adsorption process utilizing molecular sieves has been developed for landfill gas application. However, contamination of the sieves by water, butane and heavier compounds greatly reduces the capacity of the sieves to remove carbon dioxide, requiring high temperatures at low pressures to regenerate the sieves. The loss of methane by this method may range from 15 to 25 percent, which should be considered in an economic evaluation.

Reverse osmosis systems using semi-permeable membranes have been proposed for the removal of carbon dioxide from landfill gas. However, the process is highly temperature sensitive, with possible damage to the membranes. Methane loss would likely range from 22 to 28 percent. The feasibility of this treatment process for landfill gas application is questionable.

Absorption methods may be classified into three groups:

1) organic solvents
2) alkaline salt solutions
3) alkanolamines

Several organic solvent processes have been developed, of which the Selexol process is one of the most successful (Love, 1990). To achieve the degree of treatment required to satisfy natural gas pipeline standards, a series of two Selexol units are required (Hernandez, 1990). The first Selexol unit removes water and toxins from the gas. The pretreated gas exits the top of the first absorber and flows to the absorber of the secondary Selexol unit. The second absorber effectively removes the bulk quantity of carbon dioxide, which has a solubility 15 times greater than methane (see Table 2.2),

producing a purified high BTU gas suitable for assimilation into the natural gas pipeline network. The carbon dioxide rich solvent is then flashed to a lower pressure, releasing any absorbed methane which is recycled to an intermediate stage of the process. The solvent is flashed again to remove the carbon dioxide, which may be marketed as a secondary product. The regenerated Selexol solvent is recycled to the top of the absorber, following refrigeration.

An alternative treatment system configuration is to utilize the EG/refrigeration process for pretreatment of the landfill gas to remove water and toxins, followed by a secondary Selexol unit for the removal of carbon dioxide.

Studies indicate the Selexol process has the highest methane recovery efficiency of 90 percent (Love, 1990).

Absorption processes utilizing alkaline salt solutions are not as suitable for landfill gas application. Some alkanolamine processes, though, have demonstrated effective treatment and removal of carbon dioxide, including such alkanolamines as MEA (monethanolamine), DEA (diethanolamine), DGA (diglycolamine) and MDEA (methyldiethanolamine). The MDEA process uses stage flashing for regeneration similar to the Selexol process and has a methane recovery efficiency of about 89 percent (Love, 1990).

In many cases, the high BTU gas produced by operational landfill gas treatment facilities is shy of the gas industry standard heating value of 37.3 MJ/m^3 (1000 BTU/scf). This is generally a result of nitrogen present in the treated gas, which can substantially reduce the heating value. Since the removal of nitrogen requires extremely low cryogenic levels, which are uneconomical and impractical to attain, special contracts have been obtained with gas utilities permitting heating values as low as 36.1 MJ/m^3 (970 BTU/scf) (Love, 1990). An alternative is to spike the gas with propane to raise the heating value over 37.3 MJ/m^3 (1000 BTU/scf).

An additional requirement for assimilation of high BTU gas in the natural gas pipeline network is compression of the gas to a pressure of 2069 kPa (300 psig) or higher (Hernandez, 1990).

ELECTRICAL POWER GENERATION TECHNOLOGY

Utilization of landfill gas for electrical power generation is often the most viable mode of utilization in the absence of a local market for medium BTU gas, since electricity produced can be interconnected to the power grid. Power generation technology comprises of landfill gas pretreatment followed by electrical power generation by one of two methods:

1) reciprocating engines
2) turbines

Reciprocating engines require lower landfill gas recovery rates to effectively generate electricity. However, where gas recovery rates are sufficiently high, turbine technology may provide a less expensive method for electrical power generation on a per kW basis.

The components of an electrical power generation facility utilizing landfill gas are essentially the same for either reciprocating engines or turbines. The components include:

1) pretreatment - removes water and toxins
2) gas compression - pressurizes gas for injection into engine/turbine
3) engine/turbine - converts gas BTU energy to mechanical energy
4) alternator - converts mechanical energy to electrical energy
5) transformer - steps up voltage required for grid interconnection
6) grid interconnection - connects generated electricity to power grid

The components are discussed in relation to reciprocating engine and turbine technology. In the case of steam turbines, an additional step is required: boilers are fired with landfill gas to produce steam to drive the turbine.

RECIPROCATING ENGINES

Application of reciprocating engines to landfill gas for electric power generation requires some pretreatment of the landfill gas as well as modifications to the engines, since saturated raw landfill gas containing trace contaminants creates a very harsh and corrosive environment, preventing effective operation of the reciprocating engine. Table 2.1 shows a typical landfill gas composition and characteristics.

Pretreatment

Specific problems encountered in the operation of reciprocating engines utilizing landfill gas include corrosion caused by hydrogen sulfide, hydrochloric and hydrofluoric acids and other organic and carbonic acids. In addition, silica particulates in the gas coagulate in combustion causing abrasive wear of engine parts (Chadwick, 1989). Several pretreatment processes may be employed to minimize the problems encountered.

Partial removal of water from the landfill gas can be achieved using a chilling process. Additional removal of water and other contaminants is possible using absorption methods such as the Selexol process and EG/refrigeration process.

Caterpillar Engine Division, a major supplier of reciprocating engines for landfill gas application, have established fuel quality standards necessary for successful engine operation (Chadwick, 1989). Maximum level of hydrogen sulfide allowed in the fuel gas is 44.9 μg/kJ (47.4 μg/BTU). Chlorine and fluorine levels cannot exceed 37.9 μg/kJ (40 μg/BTU) while moisture content is not to exceed 1.84 g/m^3 (115 lbs/MMscf).

In addition, abrasive wear of equipment can be substantially reduced by filtering the gas. Caterpillar engine standards require 100 percent removal of particulates greater than 1.0 micron diameter and 98 percent removal of particulates greater than 0.4 micron diameter.

Reciprocating Engine Operation

Reciprocating engines utilize landfill gas as a fuel, converting BTU energy to mechanical energy which in turn is converted to electrical energy by an alternator.

Reciprocating engines have been designed to operate under a range of gas flowrates and gas inlet pressures. An increase in the fuel consumption rate results in higher power output. An increase of the inlet gas pressure results in lower NOx emission levels. At typical landfill operations, the gas fuel heating value ranges from 14.9 to 20.5 MJ/m^3 (400 to 550 BTU/scf).

Experience gained from caterpillar engine operations utilizing landfill gas indicate that best energy conversion efficiencies are achieved for fuel gas heating values ranging from 16.8 to 20.5 MJ/m^3 (450 to 550 BTU/scf) and that heating values should not drop below 14.9 MJ/m^3 (400 BTU/scf). Net energy conversion efficiencies typically range from 27 to 32 percent. Parasitic power requirements may vary from 4 to 10 percent of the power output.

Table 2.3 provides energy conversion data for several Caterpillar reciprocating engines (adapted from Chadwick, 1989). Table 2.4 gives additional technical features for Caterpillar 3516 low/high pressure reciprocating engine generators which are specifically designed for landfill application (adapted from Wolfe and Maxwell, 1990).

Table 2.3
Energy Conversion Data for Caterpillar Reciprocating Engine Generators

Engine Model	Rating (kW)	Fuel Consumption* (m^3/s)	Heat Rate (kW)	Conversion Efficiency	
				Total (%)	Net** (%)
Caterpillar 3306 SINA	92	0.018	310	29.6	26.6
Caterpillar 3306 SIT	125	0.022	392	31.9	28.7
Caterpillar 3408 SITA	290	0.052	937	31.0	27.9
Caterpillar 3412 SITA	430	0.079	1,405	30.6	27.5
Caterpillar 3516 SITA					
• Low Pressure	800	0.15	2,635	30.4	29.2
• High Pressure	800	0.15	2,635	30.4	27.7

* Assumes gas heating value = 480 BTU/scf
** Assumes parasitic power requirements = 10 percent of engine rating with the exception of Caterpillar 3516 SITA low and high pressure engines.
Adapted from Chadwick, 1989

Table 2.4
Technical Features
Caterpillar 3516 Low/High Pressure Reciprocating Engine Generators

Feature	Caterpillar 3516 Low Pressure Reciprocating Engine Generator	Caterpillar 3516 High Pressure Reciprocating Engine Generator
Landfill Gas Flow	0.15 m^3/s	1.15 m^3/s
Fuel Gas Pressure	13.8 kPa	241 kPa
Heat Rate	2635 kW	2635 kW
Gross Power Output	800 kW	800 kW
Parasitic Power Use by Compressor	30 kW	70 kW
Net Power Output	770 kW	730 kW
Net Conversion Efficiency	29.2 %	27.7 %
Emissions:		
NOx	13.6 kg/hr	5.6 kg/hr
CO	4.9 kg/hr	2.02 kg/hr

* Assumes gas heating value = 17.9 MJ/m^3 (480 BTU/scf)
Adapted from Wolfe and Maxwell, 1990.

Review of Table 2.3 shows that landfill gas recovery rates may range from 0.018 m^3/s to (37 cfm) 0.15 m^3/s (312 cfm) to successfully operate a reciprocating engine. However, experience gained by Waste Management of North America indicates that for a landfill gas utilization project to be economically viable, gas recovery rates must be sufficient to support two Caterpillar 3516 SITA reciprocating engines (Wolfe and Maxwell, 1990).

Power Grid Interconnection

Power grid interconnection requires a step up transformer, relays, a dedicated transmission line and other electrical devices and connections. The minimum interconnection cost is approximately $200,000 and may exceed one to two million depending on the length of dedicated transmission line required and other equipment requirements.

TURBINES

Where landfill gas recovery rates are sufficient, turbines are generally preferred over reciprocating engines for generating electrical power. Although turbines may have a lower energy conversion efficiency, the cost per kW generated is lower. However, if sufficient landfill gas supply cannot be maintained, reciprocating engines may be preferred since turbines operate very poorly at part load. A Centaur turbine at 80 percent of fuel load will only provide 60 percent electrical output (Wolfe and Maxwell, 1990).

Gas turbines and steam turbines are utilized in the landfill gas industry for electrical power generation. Gas turbines use landfill gas directly as a fuel to drive the turbine. This requires some pretreatment of the gas to reduce the maintenance requirements of the turbine. Steam turbines are driven by steam produced by landfill gas fired boilers. Since boilers can operate under harsher conditions than gas turbines while requiring less maintenance, a steam turbine operation requires less gas pretreatment than a gas turbine operation.

Pretreatment

Pretreatment of the recovered landfill gas is required to minimize corrosion and abrasion problems encountered utilizing landfill gas as a fuel for a gas turbine. The presence of water, carbon dioxide, halide compounds and other contaminants in the landfill gas result in the formation of hydrochloric acids, carbonic acid and other organic acids. Hydrogen sulfide also causes corrosion.

Various methods are available for pretreatment of the landfill gas. Methods include chilling to remove water and absorption processes to remove other contaminants. These methods are discussed further under sub-section heading Medium BTU Gas Technology.

A steam turbine and boiler system may be able to operate successfully utilizing unprocessed landfill gas with minimal water removal.

Turbine Operation

Operation of gas turbine generators convert BTU energy of the fuel gas into electricity which can be interconnected to the power grid. The fuel consumption rates of turbines are considerably higher than for reciprocating engines. The Solar 4500 Centaur turbine generator, employed at some Waste Management of North America landfill gas utilization projects, requires a landfill gas flow of 0.69 m^3/s (1459 cfm) assuming a heating value of 17.9 MJ/m^3 (480 BTU/scf) and a fuel gas pressure of 1,103 kPa (160 psig). Table 2.5 provides additional technical features of the Centaur turbine (adapted from Wolfe and Maxwell, 1990).

Table 2.5 Technical Features Solar 4500 Centaur Turbine Generator	
Feature	**Solar 4500 - Centaur Turbine Generator**
Landfill Gas Flow*	0.69 m^3/s
Fuel Gas Pressure	1,103 kPa
Heat Rate	12,300 kW
Gross Power Output	3,200 kW
Parasitic Power Use By Compressor	500 kW
Net Power Output	2,700 kW
Net Conversion Efficiency	22.0%
Emissions NOx CO	 3.0 kg/hr 2.5 kg/hr

* Assuming gas heating value = 17.9 MJ/m^3 (480 BTU/scf.)
Adapted from Wolfe and Maxwell, 1990.

The high combustion temperatures of gas turbines results in the destruction of toxic compounds present in the fuel gas. The destruction efficiency of turbines lowers the NOx emission level below that of reciprocating engines (Biddle and Naylor, 1989).

Steam turbine and boiler systems require substantial landfill gas recovery rates. The system installed at the Brockwest landfill in Toronto operates with an inlet gas quantity of 4.72 m^3/s (10,000 cfm) to generate 23 MW.

Power Grid Interconnection

Power grid interconnection requires a step up transformer, relays, a dedicated transmission line and other electrical devices and connections. The minimum interconnection cost is approximately $200,000 and may exceed one to two million depending on the length of dedicated transmission line required and other equipment requirements.

Section 3
ECONOMIC AND REGULATORY CONSIDERATIONS

ECONOMIC CONSIDERATIONS

The decision to implement a landfill gas utilization scheme must be based on a careful economic evaluation of the project. Key factors that must be considered include:

1) gas recovery rates
2) duration of gas recovery
3) market conditions

Market conditions that should be considered include the proximity of medium BTU gas consumers, proximity of a natural gas pipeline network and available rates for hydropower, natural gas and other local alternative energy sources.

Prior to a detailed economic evaluation of a potential landfill gas utilization project, some general guidelines are required to assess whether a detailed evaluation should be conducted. A preliminary assessment should consider the year a landfill operation commenced, the disposal rate, the landfill capacity and whether or not a landfill gas extraction system is installed or scheduled for installation. In the case that a landfill gas extraction system is required for environmental control, the economics for a landfill gas utilization scheme are significantly improved.

Several rules of thumb are used in the industry to initially assess the potential for landfill gas utilization. Although these rules are based primarily on U.S. experience, they have been used in conjunction with available information of operational systems to establish preliminary guidelines for assessing landfill gas utilization potential. Table 3.1 presents a set of guidelines. A low, moderate or high potential for each of three landfill gas utilization modes is assigned for a specified landfill capacity. Landfill gas recovery rates are also provided based on 80 percent collection efficiency for low, average, and high production rates given in Table 1.1. The recovery rates are also the maximum rates expected for the specified landfill capacity, since they are calculated assuming all refuse resident in the landfill are generating gas at the assumed production rate. The guidelines do not consider disposal rates or regional variations in economic climate such as hydro rates and should be treated as very approximate and preliminary. The guidelines assume an availability of consumers for each mode of utilization.

Table 3.1
Guidelines to Assess Landfill Gas Utilization Potential

Landfill Capacity (million tonnes)	Landfill Gas Recovery[1]			Landfill Gas Utilization Potential[5]		
	Low[2] m^3/s (cfm)	Average[3] m^3/s (cfm)	High[4] m^3/s (cfm)	Medium BTU Gas Sales	High BTU Gas Sales	Electrical Power Generation
1	0.076 (160)	0.18 (370)	0.32 (670)	Low		
2	0.15 (320)	0.35 (740)	0.63 (1.340)	Moderate		
4	0.32 (640)	0.70 (1480)	1.27 (2.690)	High		Low
6	0.46 (970)	1.05 (2.230)	1.90 (4.030)	High	Low	Moderate
10	0.76 (1.610)	1.75 (3.710)	3.17 (6.720)	High	Moderate	High
20	1.52 (3.220)	3.5 (7.420)	6.34 (13.440)	High	High	High

Notes:
(1) Recovery efficiency is assumed to be 80% of landfill gas production rates
(2) Low landfill gas recovery rate = 2.4 m^3/tonne/year (0.04 scf/lb/year)
(3) Average landfill gas recovery rate = 5.5 m^3/tonne/year (0.09 scf/lb/year)
(4) High landfill gas recovery rate = 10 m^3/tonne/year (0.16 scf/lb/year)
(5) Utilization potential assumes availability of consumers

An additional factor to consider includes the landfill depth. It has been stated that "Landfills having greater than 1 to 2 million tonnes of refuse in place, presently being operated or recently closed, receiving or having received a significant daily quantity of waste (greater than 200 tonnes per day) and having a minimum depth of refuse no less than forty feet are feasible for considering gas recovery" (Dent and Krol, 1988).

The regional economic climates in Canada for electrical power generation projects are reflected in hydro rates and utility policies. According to Dent and Krol (1988), "Several of Canada's large utilities, most notably Ontario Hydro, have already developed policies that are supportive of alternative generation."

An economic evaluation of a landfill gas utilization scheme must consider the capital and annual costs and the potential revenue. Consideration should also be given to regulatory requirements for environmental control systems. Where environmental control is required, only the additional cost to upgrade a landfill gas extraction system from environmental control to commercial application should be considered in the economic evaluation. As a rough approximation, the cost split of a commercial gas extraction system is 40 percent environmental control and 60 percent commercial (Wolfe and Maxwell, 1990).

Table 3.2 lists the cost and revenue features that must be evaluated for the different landfill gas utilization technologies. Included under revenue are potential onsite savings from utilization of landfill gas to service onsite facilities. Electricity generated can provide power to run gas extraction equipment, leachate and handling systems and other onsite facilities. Alternatively, gas firing will produce heat for special waste drying such as sewage filter cakes, treatment of recycled and recovered materials such as scrap alloy melting, destruction of toxic wastes such as pesticides and bulk volume reduction of poorly degradable materials before landfilling to prolong site life (Manley et al, 1988).

Table 3.2
Economic Evaluation of Landfill Gas Utilization Technologies

Cost/Revenue Features	Environmental Control	Medium BTU Gas Sales	High BTU Gas Sales	Electrical Power Generation
1. Capital Costs				
Landfill gas recovery				
• extraction wells/trenches	X	X	X	X
• collection pipe networks	X	X	X	X
• blower	X	X	X	X
Landfill gas treatment				
• water removal	X	X	X	X
• toxin removal		?	X	?
• carbon dioxide removal			X	
• flaring	X	X	X	X
Energy conversion				
• equipment retrofitting		X		
• engine/turbine generators				X
Transmission				
• pipeline		X	X	
• pipeline injection			X	
• power grid interconnection				X
Engineering/approvals	X	X	X	X
2. Annual Costs				
Operation and Maintenance				
• landfill gas recovery system	X	X	X	X
• landfill gas treatment	X	X	X	X
• energy conversion equipment		X		X
• transmission assembly		X	X	X
Condensate Disposal	?	?	?	?
3. Revenue				
Offsite Sales				
• BTU gas		X	X	
• electrical power				X
• carbon dioxide			?	
Onsite Savings				
• gas firing for heat application to treat wastes	?	?	?	?
• electrical power to operate onsite facilities				?

To obtain a preliminary cost estimate for the implementation of a landfill gas utilization scheme, rules of thumb may be applied. The capital cost to install a landfill gas extraction system may be assumed to be approximately $400,000 per million tonnes ($300,000 U.S. per million tons) of refuse in place with an annual operating cost of $18,000 ($15,000 U.S.) (Wolfe and Maxwell, 1990). The capital costs to implement an electrical power generation scheme, not including gas recovery, may be assumed to be approximately $1,000 per kW installed capacity (Vogt, 1991).

REGULATORY CONSIDERATIONS

Regulations governing the implementation of a landfill gas utilization scheme must be considered with respect to approvals, but also as a factor affecting the viability of a landfill gas utilization project.

The political and regulatory climate may have an important bearing in determining the viability of a landfill utilization scheme. In the U.S. the Public Utility Regulatory Polices Act (PURPA) provides benefits to small power produces, creating a more favourable climate for the implementation of landfill gas utilization projects (Klass, 1990). No such legislation exists in Canada, although some utilities have developed policies supportive of alternative generation. In addition, Dent and Krol (1988) have reported that "In Canada, the gas utilities have a franchise right for the distribution and sale of gas. Therefore, if a local natural gas consumer wants to convert to landfill gas, it is necessary for the local utility to waive its franchise rights for the sale and distribution of gas.... In general, unless there is local political pressure to do so, the gas companies are reluctant to co-operate."

The approvals process required prior to implementation of a landfill gas utilization scheme will vary from province to province, but will typically involve several regulatory agencies. Permits are required for air emissions and building construction. Contracts with local hydro and gas utilities may be necessary for energy/gas sales. Additional site specific approvals and contracts may also be required.

In Ontario, landfill gas utilization projects require modifications to the Certificate of Approval for landfill operations issued by the Ministry of the Environment and approval under the Environment Protection Act for air emissions. A recent 23 MW landfill gas power development project also required rezoning approval from the local municipality and contractual agreements between the landfill owner, the owner/operator of the power generation facility and Ontario Hydro. The approvals process was completed over an 18 month period. The collected landfill gas condensate is mixed with leachate and discharged to the sanitary sewer and is in compliance with the sewer by-law.

Section 4
OPERATIONAL LANDFILL GAS UTILIZATION SYSTEMS

CANADA

In Canada there are few landfill gas utilization systems in operation. In Ontario there are two systems in operation and one in the planning stages. In British Columbia there are several smaller utilization systems in operation. Some of the major utilization systems are identified in Table 4.1 and described.

OTTAWA STREET LANDFILL

The Ottawa Street landfill is located in Kitchener, Ontario, and extends over an area of approximately 30 ha (75 acres). The landfill was operated from 1958 to 1978 and contains approximately two million tonnes of domestic waste (Environment Canada, 1987).

A landfill gas recovery and utilization system was installed to mitigate landfill gas migration problems at the site while providing an alternate fuel source for industrial boilers at Bestpipe, a local cement pipe manufacturing industry. The boilers utilize unprocessed landfill gas as a fuel to generate steam used in the cement curing process. The system was initially placed in operational mode at the end of 1982.

The landfill gas recovery system consists of a series of extraction wells connected by lateral and header gas lines to a gas pumping system. Drain traps are located at various intervals along the collection lines and a centrifugal separator was installed to help separate water from the landfill gas prior to entering the pumping equipment. An after cooler was installed to chill the gas following pump compression using ambient outside air. The after cooler was designed to provide 70 percent moisture removal, but was later removed from service due to corrosion problems.

A transmission line conducts the landfill gas to the Bestpipe boilers, which were converted to operate utilizing natural or landfill gas.

The landfill gas utilization system was initially designed to supply 0.18 m^3/s (375 cfm) at capacity at 30 to 40 percent methane by volume. Further investigations were carried out to increase the recovery rate. However, adequate methane levels could not be maintained.

In 1985, the Ottawa Street landfill was supplying 0.12 m^3/s (250 cfm) of landfill gas at 40 percent methane by volume, sufficient to fuel one boiler.

Table 4.1
Selection of Landfill Gas Utilization Systems in Canada

Landfill Data						Utilization Data				
Landfill Site	Tonnage (million tonnes)		Closure Year	Landfill Gas Recovery		Landfill Gas Utilization m^3/s (cfm)	Startup	Mode of Utilization	Power Generation Capacity MW	Consumer
	1991	Capacity		1991 m^3/s (cfm)	Capacity m^3/s (cfm)					
Ottawa Street, Kitchener, Ontario	2	2	1978	-	0.18 (375)	250	1984	medium BTU gas fuel for boiler - steam curing	-	Bestpipe
Richmond B.C.	-	-	-	0.14 (294)	0.33 (700)	0.14 (294)	1986	medium BTU gas fuel for cement kiln	-	Lafarge Canada Inc.
Brockwest, Metro Toronto, Ontario	15.5	16 - 18	1992 - 93	4.72 (10,000)	>4.72 (>10,000)	4.72 (10,000)	1991	electrical power generation steam turbine	23	Ontario Hydro
Keele Valley, Metro Toronto - Scenario 1	12.3	20	1993 - 94	2.83 - 3.30 (6 - 7,000)	>4.72 (>10,000)	3.78 - 4.25 (8 - 9,000)	1993 - 94	electrical power generation steam and gas turbines	25 - 30	Ontario Hydro
- Scenario 2	-	>20	-	-	-	-	-		50 - 75	Ontario Hydro

RICHMOND LANDFILL

The Richmond landfill is located in the District of Richmond, British Columbia. A landfill gas recovery and utilization system was installed to mitigate odour problems prevalent at the landfill while supplying landfill gas as a supplementary fuel to operate the rotary cement kilns at a cement kiln owned and operated by Lafarge Canada. The system has been in operation since 1986.

The landfill gas was initially recovered at a rate of approximately 0.33 m^3/s (700 cfm). The transmission line consisted of a 1.6 km vacuum line followed by a 1.6 km pressure line. A recent discussion with the cement kiln operator indicated that landfill gas was being utilized at a rate of 0.14 m^3/s (294 cfm) which provided approximately 5 percent of the energy requirements to operate one rotary kiln.

BROCKWEST LANDFILL

The Brockwest landfill gas utilization system is the largest system currently in operation in Canada. The landfill is owned and operated by Metro Toronto while the utilization system is owned and operated by Eastern Power Developers Inc. Operation commenced in 1991.

The Brockwest landfill presently has in place approximately 15.5 million tonnes of refuse and closure is anticipated for 1992 or 1993. A landfill gas extraction system has been installed to provide environmental control at the site, while supplying over 4.72 m^3/s (10,000 cfm) of landfill gas at 44 percent methane by volume to be utilized for electrical power generation.

The power plant consists of a steam turbine and two boilers. The boilers are fuelled by landfill gas to produce steam which drives the turbine generator. At capacity, the turbine generator will generate 23 MW.

With the exception of a moisture drop-out chamber, the landfill gas does not undergo pretreatment prior to fuelling the boilers. Although the capital outlay for this configuration may be greater than for a gas turbine, the maintenance required for boilers should be considerably less than gas turbines operating on unprocessed landfill gas.

To achieve interconnection with the Ontario Hydro power grid, a step up transformer is used along with a dedicated 900 m transmission line. The entire interconnection cost is approximately $750,000. The cost of the entire system, not including the landfill gas extraction system, is in the order of 20 to $25,000,000.

KEELE VALLEY LANDFILL

The Keele Valley Landfill is owned and operated by Metro Toronto and has a design capacity of approximately 20 million tonnes. Plans are currently being developed for

the construction of an electrical power generating plant. Operation of the plant is anticipated for 1993 or 1994.

The Keele Valley Landfill presently has in place approximately 12.3 million tonnes of refuse. A landfill gas extraction system has been installed to provide environmental control at the site. The gas recovery rate is expected to increase from 1.89 to between 2.83 and 3.30 m^3/s (4,000 cfm to 6 or 7,000 cfm) with recent additions to the gas extraction system. Ultimate recovery rates are expected to exceed 4.72 m^3/s (10,000 cfm). The landfill extraction system is designed with a present incineration capacity of 5.66 m^3/s (12,000 cfm) and a potential ultimate capacity of 11.33 m^3/s (24,000 cfm). The quality of landfill gas recovered is 47 to 49 percent methane by volume.

The estimated total cost for the landfill gas extraction system is approximately 7 to $8,000,000 ($350,000 to $400,000 per million tonnes in place).

The electrical power generating facility will use both steam and gas turbine generators. Based on a 20 million tonne landfill capacity, a landfill gas flow of 3.78 to 4.25 m^3/s (8 to 9,000 cfm) will be utilized to generate 25 to 30 MW. However, should the landfill capacity be increased substantially, a higher gas recovery rate may permit power generation of 50 to 75 MW.

A project life of at least 20 years is anticipated.

UNITED STATES

In 1987, a total of 50 landfill gas utilization projects were in operation in the U.S. and an additional 44 projects were scheduled for operation (Kass, 1990). Of these 94 projects, 33 are located in the states of California and New York.

Table 4.2 provides summary data for a selection of landfill gas utilization systems operational in the U.S. The gas utilization systems vary from 0.20 to 2.78 m^3/s (420 to 5,900 cfm) and include end use applications of natural gas pipeline assimilation, medium BTU gas sales to local industries and electrical power generation. The landfill gas treatment process associated with the natural gas pipeline projects listed incorporate the Selexol solvent process.

Table 4.2
Selection of Landfill Gas Systems in the U.S.

Landfill	Location	Owner/Operator	Startup	Inlet Gas Quantity m^3/s (cfm)	Treated Gas Quality MJ/m^3 (BTU/scf)	End Use
Operating Industries Landfill[1]	Monterey Park, CA	GSF Energy, Inc.	1979	2.6 (5,500)	35.4 (950)	natural gas pipeline
CID Landfill[1]	Calumet City, IL	GSF Energy, Inc.	1980	1.65 (3,500)	35.4 (950)	natural gas pipeline
Fresh Kill Landfill[1]	Staten Island, NY	GSF Energy, Inc. & Methane Dev. Corp.	1982	3.26 (6,900)	35.8 (960)	natural gas pipeline
Blue Island Landfill[1]	Blue Island, IL	GSF Energy, Inc.	1983	1.32 (2,800)	22.4 (600)	industrial user
Olinda Canyon Landfill[1]	Brea, CA	GSF Energy, Incl	1984	1.32 (2,800)	20.9 (560)	power generation
Mountain Gate Landfill[1]	Los Angeles, CA	GSF Energy, Inc.	1984	1.32 (2,800)	20.9 (560)	industrial user
McCurty Landfill[1]	Houston, TX	GSF Energy , Inc.	1987	2.60 (5,500)	35.4 (950)	natural gas pipeline
Kearny Landfill[1]	Kearny, NY	GSF Energy, Inc.	1989	2.60 (5,000)	20.5 (550)	medium BTU gas pipeline
Santa Cruz Landfill[2]	Santa Cruz, CA	City of Santa Cruz & Caterpillar Generating Partners	-	0.20 (420)	medium BTU	933 kW power generation
Crazy Horse Landfill[3]	Salinas, CA	City of Salinas & pacific Energy	1986	0.21 - 0.26 (450 - 550)	20.5 (550)	1,300 kW power generation
Marina Landfill[4]	Monterey County, CA	Monterey Regional Waste Management District & GASCO	-	0.20 (420)	medium BTU	575 - 675 kW power generation

Notes

(1) Information from Hernandez, 1990
(2) Information from Kennelly, 1989
(3) Information from Clinton, 1989
(4) Information from Myers, 1989

Section 5
SUMMARY

Landfill gas generation, resulting from anaerobic decomposition processes within landfills, provides a potential alternative energy source. Landfill gas is composed primarily of methane and carbon dioxide and typically has a heating value of 14.9 to 20.5 MJ/m^3 (400 to 550 BTU/scf).

In 1986, approximately 14.6 million tonnes of municipal solid waste were landfilled. This represents a recoverable energy potential of about 100 PJ per year (Dent and Krol, 1988). Although very little of this energy is currently being harnessed, the present trend towards larger engineered sites along with requirements for greater environmental control will improve the Canadian economic climate for the implementation of landfill gas utilization projects.

Landfill gas is typically composed of methane (40 to 60 percent by volume), carbon dioxide and trace levels of nitrogen, oxygen, hydrogen, hydrogen sulfide, hydrocarbons, chlorides and other trace compounds. Landfill gas production rates may range form 3 to 12 m^3/tonne/year (0.005 to 0.23 scf/lb/year) depending on several parameters. An average production rate is about 6.9 m^3/tonne/year (0.11 scf/lb/year) (Wolfe and Maxwell, 1990). An annual rate of decline in gas production can be estimated using a simple formula. Landfill gas recovery rates typically vary form 75 to 85 percent of the production rates.

Landfill gas extraction systems are installed at sites to provide environmental control and/or to recover landfill gas for utilization. Due to the differing design requirements of control versus commercial systems, an extraction system designed solely for environmental control may cost approximately 40 percent of a commercial extraction system which incorporates environmental control features (Wolfe and Maxwell, 1990).

Landfill gas utilization technology may be broken down into three utilization categories: medium BTU fuel, high BTU fuel and electrical power generation.

Medium BTU gas technology essentially consists of pretreatment and transmission of landfill gas for direct sale to neighbouring industries which may utilize the gas as a fuel for boilers, furnaces, kilns, and gas engines. Pretreatment may consists of simple mechanical methods to remove water or more complex methods, such as absorption processes, to achieve significant toxin removal.

High BTU gas technology provides adequate treatment to upgrade landfill gas to natural gas pipeline quality for assimilation into the natural gas pipeline network. Stages of treatment required include the removal of water, removal of toxins and bulk quantity removal of carbon dioxide. Treatment methods commonly employed in the

industry include various absorption processes. An additional potential source of revenue for high BTU gas utilization projects is the sale of carbon dioxide.

Electrical power generation technology utilizes landfill gas as a fuel to drive reciprocating engine or turbine generators for the production of electricity. Electrical power generation is often the most viable mode of utilization in the absence of a local market for medium BTU gas, since electricity can be interconnected to the power grid. To reduce operational problems caused by the corrosive nature of raw landfill gas, some level of pretreatment is generally recommended. In the case of steam turbines which utilize boilers fired with landfill gas, minimal pretreatment is required due to the relatively low maintenance requirements of boilers.

Key factors to be considered in an economic evaluation of a landfill gas utilization project include gas recovery rates, duration of gas recovery, market conditions and project costs. Prior to a detailed economic evaluation, a preliminary assessment should be conducted which should consider the landfill age, disposal rate, landfill capacity, tonnage in place, and whether or not a landfill gas extraction system is installed or scheduled for installation. In the case that a gas extraction system is required for environmental control, the economics for a landfill gas utilization scheme are significantly improved.

As a general rule of thumb, it has been stated that "Landfills having greater than one to two million tonnes of refuse in place, presently being operated or recently closed, receiving or having received a significant daily quantity of waste (greater than 200 tonnes per day) and having a minimum depth of refuse no less than forty feet are feasible for considering gas recovery" (Dent and Krol, 1988).

The approvals process required prior to implementation of a landfill gas utilization scheme will vary from province to province, but will typically involve several regulatory agencies. Permits are required for air emissions and building construction. Contracts with local hydro and gas utilities may be necessary for energy/gas sales. Additional site specific approvals and contracts may also be required.

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VOLUME II

OVERVIEW OF BIOGAS UTILIZATION AND ENERGY RECOVERY IN THE PULP AND PAPER INDUSTRY

ABSTRACT

Treatment of pulp and paper effluents to remove biochemical oxygen demand (BOD), total suspended solids (TSS) and effluent toxicity is required for almost all direct discharges to surface water in North America.

Treatment of pulp and paper mill wastewaters for BOD removal is most often accomplished by aerobic treatment processes. However, these processes are typically energy intensive and incur substantial cost for sludge handling and disposal. Because of the rising costs of energy and sludge disposal, attention has focused in recent years on anaerobic treatment processes which offer benefits in both of these areas.

This paper presents an overview of anaerobic treatment, including advantages and disadvantages, competing anaerobic technologies, and case studies of anaerobic applications, energy recovery and utilization practices that have been used in the pulp and paper industry. Its objective is to alert plant managers and engineers to the applicability and advantages of anaerobic treatment and energy recovery in planning wastewater treatment plant upgrades.

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INTRODUCTION

Treatment of pulp and paper effluents to remove biochemical oxygen demand (BOD) and total suspended solids (TSS) is required for almost all direct discharges to surface water in North America. In addition, limits may apply for toxicity or specific organic and inorganic materials. Requirements vary considerably for indirect discharge of wastewater to publicly owned treatment works (POTW) depending on POTW capacity and local requirements. Often POTWs will levy a surcharge on industrial BOD and TSS discharges and will also limit discharges of specific organic and inorganic materials.

Secondary treatment of pulp and paper mill wastewaters for BOD removal is most often accomplished by aerobic treatment processes. However, these processes are typically energy intensive and incur substantial cost for sludge handling and disposal. Because of the rising costs of energy and sludge disposal, attention has focused in recent years on anaerobic treatment processes which offers benefits in both of these areas. In the pulp and paper industry, there are at least 28 full-scale anaerobic installations currently operating or under construction of which four are in Canada and four are in the United States.

This paper presents an overview of anaerobic treatment, including advantages and disadvantages, competing anaerobic technologies, and case studies of anaerobic applications, energy recovery and utilization practices that have been used in the pulp and paper industry. Its objective is to alert plant managers and engineers to the applicability and advantages of anaerobic treatment to treating mill waste streams and to encourage the consideration of anaerobic treatment and energy recovery in planning wastewater treatment plant upgrades.

OVERVIEW OF ANAEROBIC TREATMENT

The pulping of wood or other cellulosic material, whether done chemically or mechanically, results in the solubilization of organic materials such as lignin, carbohydrates, organic acids, alcohols, and inorganic ash. In anaerobic treatment, these wastewater constituents are metabolized by groups of specialized bacteria that break down complex materials to progressively simpler and smaller compounds. The end products are methane gas and carbon dioxide. The bacteria can be thought of as a self regenerating process catalyst. Anaerobic reactions are weakly exothermic with the excess energy produced going into heat and production of additional bacteria.

Up to 80 percent of the energy contained in the chemical oxygen demand removed from the process wastewater is recovered as methane (low energy natural gas) in the biogas produced. The remaining energy is used for reproduction of the anaerobic

bacteria (sludge production) or wasted as the heat byproduct of the anaerobic reactions. In contrast, the activated sludge process transforms all of the chemical oxygen demand in the wastewater to either additional bacteria (sludge production) or to waste heat.

As with the activated sludge process, disposal is required for excess biological solids produced. Typical anaerobic sludge production rates are one-third that of aerobic systems. The high cost of solids disposal and often limited solids disposal options make this aspect of anaerobic treatment attractive.

WASTEWATER CHARACTERISTICS

Mill process streams and effluents vary considerably depending on the fibre source and technology used. In general, anaerobic treatment is most applicable to waste streams with high BOD (>1000 mg/L) or COD concentration which do not contain substantial quantities of inhibitory constituents. Inhibitory constituents found in pulp and paper effluents include reduced sulphur compounds and resin acids.

Various pulp and paper waste streams that have been evaluated for treatability by anaerobic processes include:

- Kraft condensates
- Kraft bleachery effluent
- Peroxide bleachery waste and paper machine effluent
- Sulphite evaporator condensate
- Chemithermo-mechanical pulp mill effluent
- Chemical and semichemical pulp mill effluent
- Thermomechanical pulp mill effluent
- Bark landfill leachate
- Ozonated pulp mill effluent
- Secondary fibre mill effluent

A screening study of 21 Canadian pulp and paper mill process streams established that approximately 55 percent of the streams evaluated were readily treatable by anaerobic processes based on toxicity and waste strength considerations. Other streams may also be treatable with appropriate measures to protect acclimation.

In general, it was concluded that non-sulphur pulping liquors should be readily treatable anaerobically. Sulphur based pulping liquors demonstrated an inhibitory effect attributed to the presence of organic and inorganic sulphur. However, test results indicated that acclimation to the inhibitory compounds is possible.

NUTRIENTS

Inorganic nutrients and appropriate pH and alkalinity values are required to maintain a stable anaerobic process. The nutrient content and alkalinity of pulp and paper waste streams varies considerably. Anaerobic process requirements for the macro nutrients nitrogen and phosphorus requirements are typically lower than those for aerobic treatment. Thus, anaerobic treatment may provide some savings in nutrient costs for nutrient deficient wastewaters.

Micronutrients, including iron, nickel, cobalt, molybdenum, and selenium, are often available in adequate amounts in water supplies and as the result of pipe and equipment corrosion. An inexpensive wastewater analysis will indicate whether nutrients are lacking in the wastewater.

PROCESS CONSIDERATIONS

TREATMENT RATE

For anaerobic treatment systems, the specific BOD or COD removal rate is much lower than for aerobic systems (2 to 7 kg BOD_5/kg VSS/day versus 7 to 17 kg BOD_5/kg VSS/day at 35°C). Thus, to achieve similar treatment in the same volume, anaerobic systems must carry 3 to 4 times the biomass of aerobic systems. However, high rate anaerobic systems have been developed that can carry high biomass concentrations. These high rate systems can approach or equal the volumetric BOD removal rates of aerobic treatment processes.

ENERGY REQUIREMENTS

An attractive feature of anaerobic treatment is that energy requirements are low relative to aerobic treatment processes. Energy requirements typically include electricity for pumps and mixers, and steam for preheating influent wastewater. Since the process is not aerobic, there is no energy cost for blowers or surface aerators. Mixing is frequently accomplished by the configuration of the reactor and the flow of gas generated so that mechanical mixing requirements are small.

BIOGAS PRODUCTION AND USE

Biogas is typically 50-75 percent methane with the balance carbon dioxide. Small amounts of hydrogen sulphide may be present if sulphur species are present in the

wastewater. Methane gas is produced by anaerobic treatment at approximately 0.35 m^3 per kg chemical oxygen demand removed. The energy content of the biogas is typically 20 to 25,000 kj/m^3.

Major concerns of the biogas collection and storage system are safety, storage, collection system moisture removal, and end-use gas quality requirements. Prevention of air from entering the collection system and isolation of the collection system from ignition sources are two important concerns. Sufficient gas storage is typically provided in the anaerobic reactor so that sludge removal will not result in entry of large amounts of air. Flame arresters are placed close to ignition sources (waste gas burner, boiler, or engine) to minimize the potential for flashback to damage the system.

Gas leaving the process is almost saturated with water at a temperature near the treatment process operating temperature. Drip traps and accumulators are provided to remove moisture prior to check valves, relief valves, gas meters, and pressure regulators. Pipes are sloped to drain condensate to drip traps or accumulators.

Gas storage is provided in the anaerobic reactor and often in an external storage tank. Both gravity and pressure storage tanks have been used. Blowers and compressors have been used to compress and transport gas depending on the nature of the end-use requirements.

Biogas can often be burned in a low pressure boiler or flared without treatment. However, if hydrogen sulphide is present in the biogas, it will be converted to sulphuric acid which can corrode burner tips, boiler tubes, and engine internals. To protect against condensation in the boiler fire tubes and stack, the water temperature should be maintained above 71°C. Gas scrubbers must be employed if biogas is to be burned in an internal combustion engine of a gas turbine and has a hydrogen sulphide content greater than 0.3 percent. Gas scrubbers include both the wet-type with a dilute bleach solution as the working solution or the dry type with an iron based media.

TEMPERATURE

Optimum operating temperature for anaerobic systems is in the range 30 to 36°C. Attempts to speed up the anaerobic process by operating at temperatures as high as 60°C have been investigated, but few full-scale systems operate in this range. Operating at temperatures lower than optimum, slows down the rates of anaerobic reactions and effectively increases the treatment volume required for a given waste strength and flow.

pH AND ALKALINITY

The pH optimum for anaerobic systems is between 7.0 and 7.5. Below pH 6.0 and above pH 9.0, methane gas production may cease to occur. Bicarbonate alkalinity in the range 1,000 to 1,500 mg/L (as $CaCO_3$) is sufficient to buffer wastewater against changes in pH occurring as the result of organic acids produced in anaerobic processes. Whether supplemental addition of alkalinity (commonly caustic soda or soda ash) would be necessary would depend on the wastewater stream characteristics.

INHIBITION

Certain compounds can inhibit aerobic and anaerobic processes. Because of the slow metabolism of anaerobic organisms, however, inhibition can last much longer in anaerobic systems. Anaerobic bacteria have considerable capacity to acclimate to and metabolize a variety of toxic substrates. Inhibitory compounds and conditions that are of potential concern in anaerobic treatment of pulp and paper process wastewaters include:

- Inorganic sulphur compounds
- Oxidants
- Volatile organic acids
- Heavy metals
- Wood extractives including resin acids
- Organic chelating agents.

Toxic effects of these substances can be mitigated by several approaches including removal of the toxicant prior to treatment, dilution, chemical conversion, and microbial acclimation.

TYPES OF ANAEROBIC SYSTEMS

Anaerobic systems are typically used to pretreat high strength, low flow wastewater prior to polishing with aerobic treatment. Four anaerobic process configurations have been demonstrated to treat various pulp and paper mill effluents in full-scale facilities. These configurations are:

- Anaerobic lagoon
- Anaerobic contact
- Upflow anaerobic sludge blanket
- Anaerobic filter

ANAEROBIC LAGOON

Anaerobic lagoons are typically lined earthen basins covered with a synthetic membrane to maintain anoxic conditions, collect gas, and control odours. They can be configured as a single cell or multiple cells in series or parallel operation. Influent wastewater is mixed with inorganic nutrients and neutralized if necessary to maintain adequate pH in the lagoon. Some mixing of the bacterial solids occurs through gas generation which can be enhanced with intermittent use of low speed mixers or solids recycle. Biogas is typically collected at multiple point under the cover under slight negative pressure to prevent bubbling and lifting of the cover.

In the pulp and paper industry, anaerobic lagoons have been used to treat wastewaters from secondary fibre mills. Anaerobic lagoons are most applicable to wastewaters that have a low concentration of non-degradable suspended solids, since these will settle out and accumulate in the reactor, requiring that the solids be removed at some point. A prerequisite of lagoons is sufficient area for installation since they are typically sized for a hydraulic retention time of 7 to 10 days. Temperature is also a concern due to the large exposed surface area.

An advantage of anaerobic lagoons is their ability to handle degradable solids. With suitable design, solids retention can be on the order of months, providing the residence time necessary for the slow solids hydrolysis reactions. Thus, anaerobic lagoons are appropriate for high fibre wastewaters or for co-disposal of process wastewater and waste activated sludge. Because of their size, anaerobic lagoons also provide equalization which buffers slug loads of high BOD wastewater. Other advantages include simplicity of operation and lower capital and operating costs compared to high rate anaerobic systems.

ANAEROBIC CONTACT PROCESS

The anaerobic contact process is analogous to the activated sludge process. After nutrient addition and pH adjustment as needed, wastewater enters a completely mixed anaerobic reactor containing biological solids. From the anaerobic reactor the treated wastewater and biological solids flow to a degasification chamber to separate entrained methane and carbon dioxide from biological solids. A solids separation device separates suspended solids from the reactor effluent with the solids recycled back to the reactor.

Conventional and lamella clarifiers and dissolved air flotation units have been used for solids separation at full-scale installations. Solids recycle enables the anaerobic reactor to operate at a higher solids concentration than would a lagoon with a concomitant increase in the allowable volumetric loading. Degasification is critical to solids separation and is often accomplished by applying a vacuum to a splash plate or other high surface area apparatus upstream of the solids separation device.

Anaerobic contact systems are most appropriate where decomposition of degradable suspended solids, such as cellulose fibres or waste activated sludge is required. Because suspended solids in the feed are separated from the effluent wastewater and recycled to the anaerobic reactor along with the biological solids, the residence time of these solids can be extended to the duration necessary for their hydrolysis. A disadvantage of the anaerobic contact process is that it typically does not achieve the volumetric loadings of other high rate anaerobic processes and thus requires a larger reactor size. This process has been applied to groundwood mill effluent, thermomechanical mill effluent, chemi-thermomechanical mill effluent, and sulphite condensates.

UPFLOW ANAEROBIC SLUDGE BLANKET PROCESS

In an upflow anaerobic sludge blanket reactor (UASB), anaerobic bacteria form dense granules that settle and remain in a bed at the bottom of the reactor. The suspended solids concentration of the sludge bed is commonly 8 to 13 percent dry solids with a volatile content of 60 to 90 percent. After nutrient addition and pH adjustment as needed, influent wastewater is evenly distributed over the bottom of the UASB reactor. The upward flow of wastewater and gas generation bring the granules into contact with the soluble organics. A flocculent sludge blanket forms above the bed, typically with 3,000 to 10,000 mg/L dry solids. A device at the top of the reactor separates solids, gas, and effluent wastewater. Recycle of effluent is normally used to maintain a constant hydraulic loading on the reactor and to dilute the influent wastewater as needed.

The UASB is a high rate process, having volumetric loadings 3 to 5 times greater than the anaerobic contact process and 10 to 20 times greater than the anaerobic lagoon. However, UASB reactors are not effective in removing degradable suspended solids. Suspended solids such as cellulosic fibres and waste activated sludge typically have settleabilities poorer than the UASB particles and are not retained in the reactor at typical hydraulic loadings. UASB technology has been applied to effluents from boxboard mills corrugating mills, tissue mills, neutral sulphite semi-chemical (NSSC) pulp mills, and combined NSSC/CTMP and NSSC/TMP pulp mills.

ANAEROBIC FILTER

The anaerobic filter consists of a reactor vessel filled with fixed media, which provide support for development of active biomass. Attachment of bacterial solids to the media reduces the risk of washout of the biomass. Biomass thickness and total quantity are influenced by process configuration and characteristics of the support media. Recycle is commonly employed to minimize pH gradients, maintain hydraulic conditions that assure good flow distribution and minimize short circuiting, and minimize toxicity effects resulting from high influent concentration. Anaerobic filters have been designed with both upflow and downflow modes of operation. In the upflow mode, high biomass concentrations can be developed because suspended biomass becomes entrapped in the

media. However, entrapment of solids can also lead to plugging which is a major drawback of upflow anaerobic filters.

Anaerobic filters are not used in pulp and paper applications as widely as the other technologies. There is one full-scale pulp and paper application in Europe, but none in North America. Anaerobic filters can attain similar volumetric loadings to UASB reactors. Like UASB reactors, they do not handle solids well, tending to plug in the upflow mode and passing solids without sufficient retention time for degradation in the downflow mode. One potential advantage of downflow anaerobic filters for pulp and paper applications is that they allow for the separation of the faster growing, sulphur reducing bacteria in the upper portion of the fixed media from the slower growing methane forming bacteria. Thus the downflow filter could operate as a two stage reactor and may be able to tolerate much higher inorganic sulphur levels at lower degradable COD to inorganic sulphur ratios than other single stage anaerobic processes.

CASE STUDIES

NIAGARA OF WISCONSIN

Niagara of Wisconsin Paper Corporation produces 260 tpd of groundwood pulp and 750 tpd of coated paper at their mill in Niagara, Wisconsin. An upgrade of their existing aerobic wastewater treatment facility was required to meet a stricter waste load allocation and to accommodate a production capacity expansion. Two streams, bleaching whitewater and excess paper machine whitewater were identified as having high strength and low flow suitable for anaerobic treatment. These two streams account for 30 percent of the total mill BOD load but only 10 percent of the flow. It was proposed to anaerobically pretreat these streams along with waste activated sludge to reduce sludge handling and disposal requirements.

The anaerobic contact process was selected because of the high suspended solids content of the process wastewater and the desire to treat waste activated sludge. The anaerobic facility consists of a neutralization tank, two 9,300 m^3 reactors, a degasification tank, and conventional clarifier. Effluent from the anaerobic system is discharged to the activated sludge system for polishing. Startup was performed without upset over a period of 5 months in 1986. The process has consistently removed greater than 90 percent of the influent BOD at a loading of 1.6 kg COD/m^3/day.

Biogas is produced at an average rate of 2,000 m^3/day and methane content of 75 percent and is used in the plant boilers where it satisfies approximately 2.5 percent of plant energy usage. Gas is piped directly from the gas storage dome to the boilers. No gas treatment or conditioning is used other than moisture traps.

STONE CONSOLIDATED

Stone Consolidated operates a combined CTMP and NSSC mill in Bathurst. New Brunswick. The wastewater treatment system was designed as a combined anaerobic/ aerobic system. The mill produces 454 tons per day of corrugated medium and 510 tons per day of chemi-thermomechanical pulp of which 270 tons is bleached. Wastewater flow to be anaerobically treated is 15.700 m^3/day with COD and BOD loads of 11,750 kg/day and 5,100 kg/day, respectively. The treatment objective for the facility is to reduce the total BOD_5 discharge by 75 percent and achieve an effluent that is not toxic to fish.

System components include a cooling tower to cool the influent below 40°C. influent equalization, pH neutralization and nutrient addition, a UASB reactor, and, finally, a 24-hour aerated stabilization basin. The anaerobic treatment system was started up in 1988. The major hurdle with the startup was securing enough seed sludge from another facility. Seed sludge was collected and stored in the sludge storage tank until enough was accumulated to start one of the two reactors. This reactor was then operated until enough additional sludge had been generated to start the second reactor. The anaerobic system achieves a 60 percent COD reduction.

Gas production averages 30,000 m^3 per day. Approximately 75 percent of the gas is used to fire the CTMP flash drier which accounts for 50 percent of the drier fuel requirement. The balance of the gas is flared. However, the mill is evaluating uses for the balance of the biogas.

The gas handling system includes a 100 cubic meter gas storage vessel, compressors, and condensate traps and appropriate safety equipment. The 1.5 percent hydrogen sulphide in the biogas does not substantially increase the sulphur emissions from the plant compared to the bunker C fuel oil it displaces. However, the high hydrogen sulphide content has required the installation of hydrogen sulphide monitors throughout the wastewater treatment facility in addition to combustion monitors.

QUESNAL RIVER PULP

The Quesnal River Pulp Company, located in Quesnal River, British Columbia, alternately campaigns thermomechanical and bleached chemi-thermomechanical pulp. Streams discharged to the treatment system include white water, chip conditioning waste water, and floor trench flow. Loadings are 63,000 kg/d of COD and 25,500 kg/d of BOD based on 950 tpd of TMP and 141,500 kg/d of COD and 58,400 kg/d of BOD based on BCTMP. An existing aerated lagoon was unable to achieve provincial permit limits even with a doubling of the aeration capacity.

The full-scale treatment system consists of primary clarification for solids removal, anaerobic treatment using UASB reactors, and aerobic polishing. Startup began in

1988 and lasted less than one month by the end of which all mill effluent was directed through the anaerobic treatment plant. Inhibition by resin acids from the high fraction of pine used at the mill and the aggressive extraction procedure used in BCTMP pulping was reduced by clarified effluent recycle and dissolved air flotation to remove particulate bound resin acids. BOD reductions are 40 to 60 percent for the anaerobic reactors and 80 to 90 percent for the entire system. The combined anaerobic/aerobic effluent meets fish toxicity requirements. Solids from primary clarification are dewatered and landfilled.

Biogas produced in the anaerobic reactor is a mixture of 75 percent methane, 1.5 to 3.5 percent hydrogen sulphide with the balance carbon dioxide. A 70 cubic meter membrane type gas holder serves as a surge tank to ensure even gas flow to the gas handling equipment. A caustic scrubber is used to absorb hydrogen sulphide before the gas is flared.

ALASKA PULP

Alaska Pulp Corporation operates a dissolving pulp mill in Sitka, Alaska. A Consent Decree signed gave the mill 24 months to meet a 9,000 kg/day reduction in BOD loading. Concerns on expanding the existing activated sludge system were sludge production, which would have required construction of a new hog fuel boiler for sludge incineration. High strength, low flow mill streams identified as candidates for anaerobic treatment were evaporator condensate and caustic extraction liquor. Both these streams are warm and would not have to be heated for anaerobic treatment. Flow and COD loading to the anaerobic facility are 14,000 m^3/day and 170,000 kg/day, respectively.

The full-scale anaerobic treatment system consists of two anaerobic contact reactors, four lamella separators, and a gas handling facility. The facility was started up over a period of six months in 1989. Five hundred tons of anaerobically digested sludge from the Seattle Metro wastewater treatment plant were shipped to Alaska by barge, which required five voyages. The anaerobic system removes approximately 50 percent of the COD and 85 percent of the BOD, respectively.

Gas is produced at a rate of approximately 20,000 m^3/day with a methane content of 65 percent. Originally the gas was used to fire the power generation boilers. However, sulphur dioxide air emissions concerns led to switching use of the biogas to the recovery boilers. The gas constitutes a significant energy savings to the facility providing for approximately 20 percent of the mills total energy requirement and displacing an estimated 120 barrels of fuel oil per day. No conditioning of the gas is performed other than dehumidification in traps. The hydrogen sulphide content of the gas is approximately 1 to 2 percent.

INLAND CONTAINER

Inland Container Corporation operates a 350 ton per day recycling mill in Newport, Indiana. The initial treatment system consisted of two 21,000 cubic meter aerated lagoons. Increased BOD loading required an expansion of BOD reduction capabilities. Inland converted one of the two aerated lagoons to an anaerobic lagoon, moving all aeration equipment to the remaining aerated lagoon.

The anaerobic lagoon was started up in 1979 with anaerobic biomass. No cover was used for gas collection but styrofoam insulation panels were applied to the lagoon surface to retain heat during winter. The lagoon removes approximately 85 percent of the 9,000 kg/day influent BOD. Combined anaerobic/aerobic treatment efficiency is greater than 95 percent.

CONCLUSION

This paper presented five existing facilities that have successfully integrated anaerobic treatment into their wastewater treatment systems. Benefits obtained by these facilities from anaerobic treatment include:

- Net energy producer for use in plant processes
- Low sludge production and related disposal costs compared to aerobic treatment processes
- Comparable construction cost and space requirements compared to aerobic treatment processes

Energy benefits from anaerobic treatment can be substantial. Less energy is used in anaerobic processes compared to aerobic treatment since no aeration is needed and mixing requirements are low. In addition, the process converts biodegradable materials to methane gas, producing excess energy which can be used in power boilers, recovery boilers, pulp driers, and internal combustion engines. Major gas handling requirements are storage to equalize flow variability, compressors to transport the gas, and moisture traps.

The presence of elevated levels of hydrogen sulphide in the gas leads to concern over safety and sulphur dioxide air emissions. However, these concerns can be overcome. Although there are relatively few pulp and paper facilities using anaerobic treatment processes there is extensive gas handling experience in the food processing industry and in sludge digesters at municipal wastewater treatment plants.

The number of installations in the pulp and paper industry continues to grow as the operating experience bears out the applicability of anaerobic treatment to pulp and paper wastewaters.

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VOLUME III

OVERVIEW OF BIOGAS UTILIZATION AND ENERGY RECOVERY IN THE FOOD PROCESSING INDUSTRY

ABSTRACT

Treatment of food processing wastewater effluents to remove biochemical oxygen demand (BOD) and total suspended solids (TSS) is required for almost all direct discharges to surface water in North America. In addition, many municipalities impose limits on BOD and TSS as well as specific organic and inorganic materials and toxic components in wastewaters that are discharged to publicly owned wastewater treatment plants (POWTs).

The high BOD low flow streams in many food processing effluents make anaerobic treatment an economically attractive alternative to traditional aerobic treatment processes. This paper presents an overview of anaerobic treatment, including advantages and disadvantages, competing anaerobic technologies, case studies of anaerobic applications, and energy recovery and utilization practices that have been used in the food processing industry. Its objective is to alert plant managers and engineers to the applicability and advantages of anaerobic treatment to treating plant waste streams, and to encourage the consideration of anaerobic treatment and energy recovery in planning wastewater treatment plant upgrades.

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INTRODUCTION

Treatment of food processing wastewater effluents to remove biochemical oxygen demand (BOD) and total suspended solids (TSS) is required for almost all direct discharges to surface water in North America. In addition, limits may apply for toxicity or specific organic and inorganic materials. Requirements vary considerably for indirect discharge of wastewater to publicly owned treatment works (POTW) depending on POTW capacity and local requirements. Often POTWs will levy a surcharge on industrial BOD and TSS discharges and will also limit discharges of specific organic and inorganic materials.

Secondary treatment of food processing wastewaters for BOD removal is most often accomplished by aerobic treatment processes. These aerobic treatment processes usually require the supplemental addition of oxygen to the wastewater to support the relatively high bacterial growth rates necessary to degrade the organic material in the wastewater. Oxygen is usually supplied by air addition through surface aeration or submerged aeration equipment. The primary energy source for aeration is electricity. Because of the rising cost of electricity and the high projected increases in the next decade, attention has focused in recent years on anaerobic treatment processes. In the food processing industry alone there are at least seven full-scale anaerobic treatment system currently operating or under construction in Canada and 29 in the USA.

The high BOD low flow streams in many food processing effluents make anaerobic treatment an economically attractive alternative to traditional aerobic treatment processes. This paper presents an overview of anaerobic treatment, including advantages and disadvantages, competing anaerobic technologies, and case studies of anaerobic applications in the food processing industry. Its objective is to alert plant managers and engineers to the applicability and advantages of anaerobic treatment to treating plant waste streams and to encourage the consideration of anaerobic treatment in planning wastewater treatment plant upgrades.

OVERVIEW OF ANAEROBIC TREATMENT

Food processing releases sugars, starches, and cellulosic material to wastewater. These materials are broken down by the anaerobic bacteria to progressively simpler and smaller molecules. The end products of the anaerobic process are anaerobic gas and additional bacteria. The anaerobic gas is a low energy content fuel which has been used in industrial boilers, cogeneration systems (internal combustion engine with waste heat recovery), and driers.

Up to 80 percent of the energy contained in the chemical oxygen demand removed from the process wastewater is recovered as methane (low energy natural gas) in the biogas produced. The remaining energy is used for reproduction of the anaerobic bacteria (sludge production) or wasted as the heat byproduct of the anaerobic reactions. In contrast, the activated sludge process (aerobic process most commonly used) transforms all of the chemical oxygen demand in the wastewater to either additional bacteria (sludge production) or to waste heat.

As with the activated sludge process, disposal is required for excess biological solids produced. Typical anaerobic sludge production rates are one-third that of aerobic systems. The high cost of solids disposal and often limited solids disposal options make this aspect of anaerobic treatment attractive.

WASTEWATER CHARACTERISTICS

Food processing wastewater varies considerably depending on the products made and technology used. In general, anaerobic treatment is most applicable to waste streams with high BOD (>1,000 mg/L BOD_5) or COD concentration which do not contain substantial quantities of inhibitory constituents. Food processing waste streams are often ideal candidates for anaerobic treatment because they are often high strength and contain readily biodegradable sugars and starches. Inhibitory constituents found in food processing wastewaters can include reduced sulphur compounds, cleaning agents, and oxidants.

Full-scale anaerobic systems have been designed and operated for various food processing waste streams including:

- Potato processing
- Dairy products
- Oats processing
- Beet sugar
- Meat processing
- Ice Cream
- Apple processing
- Vegetable Cannery
- Yeast production
- Soft Drinks
- Fructose production
- Jams and jellies
- Corn, wheat, barley, and potato starch
- Seafood
- Beans/Pasta
- Candy
- Molasses
- Pectin production
- Brewery
- Distillery
- Coffee production
- Bakery
- Fruit Juice
- Cheese products
- Food flavourings

NUTRIENTS

Inorganic nutrients and appropriate pH and alkalinity values are required to maintain a stable anaerobic process. The nutrient content and alkalinity of food processing waste streams varies considerably. Anaerobic process requirements for the macro nutrients, nitrogen and phosphorus are typically lower than those for aerobic treatment. Thus, anaerobic treatment may provide some savings in nutrient costs for nutrient deficient wastewaters.

Micronutrients, including iron, nickel, cobalt, molybdenum, and selenium, are often available in adequate amounts in water supplies and as the result of pipe and equipment corrosion. An inexpensive wastewater analysis will indicate whether nutrients are lacking in the wastewater.

PROCESS CONSIDERATIONS

TREATMENT RATE

For anaerobic treatment systems, the specific BOD or COD removal rate is much lower than for aerobic systems (2 to 7 kg BOD_5/kg VSS/day versus 7 to 17 kg BOD_5/kg VSS/day at 35°C). Thus, to achieve similar treatment in the same volume, anaerobic systems must carry 3 to 4 times the biomass of aerobic systems. However, high rate anaerobic systems have been developed that can carry high biomass concentrations. These high rate systems can approach or equal the volumetric BOD removal rates of aerobic treatment processes.

ENERGY REQUIREMENTS

An attractive feature of anaerobic treatment is that energy requirements are low relative to aerobic treatment processes. Energy requirements typically include electricity for pumps and mixers, and steam for preheating influent wastewater. Since the process is not aerobic, there is no energy cost for blowers or surface aerators. Mixing is frequently accomplished by the configuration of the reactor and the flow of gas generated so that mechanical mixing requirements are small.

BIOGAS PRODUCTION AND USE

Biogas is typically 50 to 75 percent methane with the balance carbon dioxide. Small amounts of hydrogen sulphide may be present if sulphur species are present in the wastewater. Methane gas is produced by anaerobic treatment at approximately 0.35 m^3

per kg chemical oxygen demand removed. The energy content of the biogas is typically 20 to 25,000 kj/m^3.

Major concerns of the biogas collection and storage system are safety, storage, collection system moisture removal, and end-use gas quality requirements. Prevention of air from entering the collection system and isolation of the collection system from ignition sources are two important concerns. Sufficient gas storage is typically provided in the anaerobic reactor so that sludge removal will not result in entry of large amounts of air. Flame arresters are placed close to ignition sources (waste gas burner, boiler, or engine) to minimize the potential for flashback to damage the system.

Gas leaving the process is almost saturated with water at a temperature near the treatment process operating temperature. Drip traps and accumulators are provided to remove moisture prior to check valves, relief valves, gas meters, and pressure regulators. Pipes are sloped to drain condensate to drip traps or accumulators.

Gas storage is provided in the anaerobic reactor and often in an external storage tank. Both gravity and pressure storage tanks have been used. Blowers and compressors have been used to compress and transport gas depending on the nature of the end-use requirements.

Biogas can often be burned in a low pressure boiler or flared without treatment. However, if hydrogen sulphide is present in the biogas, it will be converted to sulphuric acid which can corrode burner tips, boiler tubes, and engine internals. To protect against condensation in the boiler fire tubes and stack, the water temperature should be maintained above 71°C. Gas scrubbers must be employed if biogas is to be burned in an internal combustion engine of a gas turbine and has a hydrogen sulphide content greater than 0.3 percent. Gas scrubbers include both the wet-type with a dilute bleach solution as the working solution or the dry type with an iron based media.

TEMPERATURE

Optimum operating temperature for anaerobic systems is in the range 30 to 36°C. Attempts to speed up the anaerobic process by operating at temperatures as high as 60°C have been investigated, but few full-scale systems operate in this range. Operating at temperatures lower than optimum, slows down the rates of anaerobic reactions and effectively increases the treatment volume required for a given waste strength and flow.

pH AND ALKALINITY

The pH optimum for anaerobic systems is between 7.0 and 7.5. Below pH 6.0 and above pH 9.0, methane gas production may cease to occur. Bicarbonate alkalinity in

the range 1,000 to 1,500 mg/L (as $CaCO_3$) is sufficient to buffer wastewater against changes in pH occurring as the result of organic acids produced in anaerobic processes. Whether supplemental addition of alkalinity (commonly caustic soda or soda ash) would be necessary would depend on the wastewater stream characteristics.

INHIBITION

Certain compounds can inhibit aerobic and anaerobic processes. Because of the slow metabolism of anaerobic organisms, however, inhibition can last much longer in anaerobic systems. Anaerobic bacteria have considerable capacity to acclimate to and metabolize a variety of toxic substrates. Inhibitory compounds and conditions that are of potential concern in anaerobic treatment of food processing wastewaters include:

- Inorganic sulphur compounds
- Oxidants
- Biocides
- Cleaning chemicals
- Volatile organic acids
- Heavy metals
- Organic chelating agents.

Toxic effects of these substances can be mitigated by several approaches including removal of the toxicant prior to treatment, dilution, chemical conversion, and microbial acclimation.

TYPES OF ANAEROBIC SYSTEMS

Four anaerobic process configurations have been demonstrated to treat various food processing effluents in full-scale facilities. These configurations are:

- Anaerobic lagoon
- Anaerobic contact
- Upflow anaerobic sludge blanket
- Anaerobic filter

ANAEROBIC LAGOON

Anaerobic lagoons are typically lined earthen basins covered with a synthetic membrane to maintain anoxic conditions, collect gas, and control odours. They can be configured as a single cell or multiple cells in series or parallel operation. Influent wastewater is mixed with inorganic nutrients and neutralized if necessary to maintain adequate pH in

the lagoon. Some mixing of the bacterial solids occurs through gas generation which can be enhanced with intermittent use of low speed mixers or solids recycle. Biogas is typically collected at multiple point under the cover under slight negative pressure to prevent bubbling and lifting of the cover.

Anaerobic lagoons have been used to treat wastewaters from a variety of industries including cornstarch production, dairies, potato processing, seafood processing, candy manufacture, and breweries. Anaerobic lagoons are most applicable to wastewaters that have a low concentration of non-degradable suspended solids, since these will settle out and accumulate in the reactor, and need to be removed at some point. A prerequisite of lagoons is sufficient area for installation since they are typically sized for a hydraulic retention time of 7 to 10 days. Temperature is also a concern due to the large exposed surface area.

An advantage of anaerobic lagoons is their ability to handle degradable solids. With suitable design, solids retention can be on the order of months, providing the residence time necessary for the slow solids hydrolysis reactions. Thus, anaerobic lagoons are appropriate for many high solids wastewaters or for co-disposal of process wastewater and waste activated sludge. Because of their size, anaerobic lagoons also provide equalization which buffers slug loads of high BOD wastewater. Other advantages include simplicity of operation and lower capital and operating costs compared to high rate anaerobic systems.

ANAEROBIC CONTACT PROCESS

The anaerobic contact process is analogous to the activated sludge process. After nutrient addition and pH adjustment as needed, wastewater enters a completely mixed anaerobic reactor containing biological solids. From the anaerobic reactor the treated wastewater and biological solids flow to a degasification chamber to separate entrained methane and carbon dioxide from biological solids. A solids separation device separates suspended solids from the reactor effluent with the solids recycled back to the reactor.

Conventional and lamella clarifiers and dissolved air flotation units have been used for solids separation at full-scale installations. Solids recycle enables the anaerobic reactor to operate at a higher solids concentration than would a lagoon with a concomitant increase in the allowable volumetric loading. Degasification is critical to solids separation and is often accomplished by applying a vacuum to a splash plate or other high surface area apparatus upstream of the solids separation device.

Anaerobic contact systems are most appropriate where decomposition of degradable suspended solids, such as cellulose fibres or waste activated sludge is required. Because suspended solids in the feed are separated from the effluent wastewater and recycled to the anaerobic reactor along with the biological solids, the residence time of these solids

can be extended to the duration necessary for their hydrolysis. A disadvantage of the anaerobic contact process is that it typically does not achieve the volumetric loadings of other high rate anaerobic processes and thus requires a larger reactor size. This process has been applied to effluents from meat packing, wheat starch production, beet sugar production, distilleries, fruit juice processing, and pectin production.

UPFLOW ANAEROBIC SLUDGE BLANKET PROCESS

The upflow anaerobic sludge blanket (UASB) process makes use of the ability of certain anaerobic bacteria to coalesce in dense granules that settle well and remain in a bed at the bottom of the reactor. The suspended solids concentration of the sludge bed is commonly 8 to 13 percent dry solids with a volatile content of 60 to 90 percent. After nutrient addition and pH adjustment as needed, influent wastewater is evenly distributed over the bottom of the UASB reactor. The upward flow of wastewater and gas generation bring the granules into contact with the soluble organics. A flocculent sludge blanket forms above the bed, typically with 3,000 to 10,000 mg/L dry solids. A device at the top of the reactor separates solids, gas, and effluent wastewater. A recycle flow is normally used to maintain a constant hydraulic loading on the reactor and to dilute the influent wastewater as needed.

UASB reactors can tolerate the highest volumetric loadings of commonly used anaerobic reactors, 3 to 5 times greater than the anaerobic contact process and 10 to 20 times greater than the anaerobic lagoon. However, UASB reactors are not effective in removing degradable suspended solids. Suspended solids such as cellulosic fibres and waste activated sludge have settleabilities poorer than the UASB particles and pass through the reactor at typical hydraulic loadings. UASB reactors have been used for treating wastewaters from breweries, vegetable canneries, cornstarch processing, potato processing, production of jams and jellies, cheese manufacture, soft drink production, yeast production, dairies and dairy products, beet sugar production, candy production, coffee production, lemon and orange peel processing, bakeries, and distilleries.

ANAEROBIC FILTER

The anaerobic filter is a reactor filled with fixed media, which provide support for development of active biomass. Attachment of bacterial solids to the media reduces the risk of washout of the biomass. Biomass thickness and total quantity are influenced by process configuration and characteristics of the support media. Recycle is commonly employed to minimize pH gradients, maintain hydraulic conditions that assure good flow distribution, and minimize toxicity effects resulting from high influent concentration. Anaerobic filters have been designed with both upflow and downflow modes of operation. In the upflow mode, higher biomass concentrations can be developed because suspended particles become entrapped in the structure of the fixed bed media.

However, entrapment of solids can also lead to plugging which is a major potential drawback of upflow anaerobic filters.

Anaerobic filters have not been widely used in food processing applications. Applications include distilleries and canned and frozen foods. Anaerobic filters can attain similar volumetric loadings to UASB reactors and, like UASB reactors, they do not handle solids well, tending to plug in the upflow mode and passing solids without sufficient retention time for degradation in the downflow mode. One potential advantage of downflow anaerobic filters for food processing waste streams containing high sulphur concentrations is that they allow for the separation of the faster growing, sulphur reducing bacteria in the upper portion of the fixed media from the slower growing methane forming bacteria. Thus the downflow filter could operate as a two stage reactor and may be able to tolerate much higher inorganic sulphur levels at lower degradable COD to inorganic sulphur ratios than other single stage anaerobic processes.

CASE STUDIES

PACKERLAND PACKING COMPANY

Packerland Packing Company, operates a high-volume beef processing/rendering plant in Green Bay, Wisconsin. High costs for physical chemical treatment and surcharges for discharge to a municipal wastewater treatment plant prompted a move to anaerobic treatment. Average flow is 3,000 m^3 per day. COD, BOD_5, and TSS loads are 23,000 kg/day, 10,300 kg/day and 8300 kg/day, respectively.

The anaerobic contact process was selected as most effective in handling the high solids loading in the influent wastewater. The facility was started up in 1987. The full-scale treatment system consists of an 1,260 m^3 equalization tank, heat exchanger, 8,900 m^3 anaerobic contact reactor, vacuum degasification tank, and 21-meter diameter conventional clarifier. The average biogas production rate is approximately 9,900 m^3 per day.

Biogas is burned in existing plant boilers to produce process steam, part of which is used to preheat the influent wastewater. Packerland estimates the energy value of the gas to be $1,200 per day. The gas handling system consists of a variable volume gas surge tank, compressor and gas storage tank (65 m^3). The compressor provides cooling and dehumidification of the gas. However, Packerland has experienced high boiler maintenance costs due to humidity and hydrogen sulphide in the biogas.

OGILVIE MILLS

Ogilvie Mills operates a wheat starch processing facility at Thunder Bay, Ontario, which pretreats its wastewater prior to discharge to a municipal wastewater treatment plant. A tightening of discharge requirements was the impetus for construction of a wastewater pretreatment facility. Anaerobic contact technology was selected over UASB technology because a pilot test had indicated that high levels of TSS in the influent waste stream caused instability in the sludge blanket.

The full-scale contact system was started up in 1982. It was originally intended to operate at typical anaerobic operating temperatures (30 to 39°C) and consists of an anaerobic contact tank, flocculation and degasification chamber, and lamella clarifiers. Effluent from the lamella clarifiers flows to an activated sludge system including a final clarifier. However, the facility was unable to achieve design loadings of 2.6 kg COD/m^3/day because of sludge settleability problems which decreased the biomass in the reactor.

In 1985, the operating temperature of the contact process was increased to 55°C (thermophilic operation) by injecting steam into the influent increased the allowable maximum loading to 4.0 kg COD/m^3/day. The major disadvantage of the higher temperature operation was an increase in odours. Solids flotation in the clarifier caused by gas production after the degasification tank caused significant solids losses from the system, preventing effective biomass recirculation. However, stable operation was achieved in spite of this condition.

The wastewater at the Thunder bay facility contains an average of 8,200 mg/L BOD_5 and 14,000 mg/L COD. The facility has a BOD_5 capacity of 7,500 kg/day and a maximum volumetric loading rate of 4 kg COD/m^3/day. Total volume of the reactor is approximately 1,800 m^3. Flow rates are typically less than 1,000 m^3 per day. Removal efficiencies for COD and BOD are 81 percent and 93 percent, respectively.

The methane yield is 0.23 m^3 methane per kg COD removed resulting in a biogas production rate of 1600 m^3 methane per day. The biogas is piped directly from the integral gas storage dome to plant boilers and generates steam in excess of that required to preheat the influent wastewater. The only gas conditioning consists of moisture traps. The biogas produced provides approximately 25 to 30 percent of total plant energy requirements or about $300/d.

HANOVER BRANDS

Hanover Brands, Inc., located in Hanover, Pennsylvania produces ten million cases of various food items annually. Products include canned and frozen vegetables, dry pack items, vegetable salads, tomato, potato, and onion products, soups, and fruit drinks. Discharge of food processing wastewater had cause problems at the local municipal

treatment plant, leading to discharge restrictions on the food processing facility resulted in construction of an anaerobic/aerobic treatment system.

The treatment system consists of heat exchangers to preheat the wastewater, a 3700 m^3 anaerobic filter containing 1,600 m^3 of plastic media at a depth of 2 meters, degasification chamber, and a conventional clarifier. Clarifier effluent is discharged to a 7.5 HRT aerobic/anaerobic stabilization lagoon followed by two 3-hour HRT polishing ponds. Gas from the anaerobic reactor is used to preheat the influent wastewater with the balance being flared.

The facility was started up over a four month period beginning in May 1986. A BOD removal efficiency of 80 percent was achieved within 6 months after startup. Loadings are 4,000 to 8,000 lb/day. BOD removals of greater than 95 percent have been achieved. Gas production averaged 2,200 m^3 per day.

ANAHEIM CITRUS PRODUCTS

Anaheim Citrus Products Company in Anaheim, California washes and dries lemon peel for pectin extraction with wastewater going to the city sewer. Average flow is 1150 m^3 per day. COD and BOD_5 concentrations are 29,000 mg/L and 18,000 mg/L, respectively. The city required wastewater pretreatment to reduce COD. Anaerobic treatment was selected because of its low sludge production, low energy consumption, and low space requirements.

The upflow anaerobic sludge blanket (UASB) system was commissioned in 1988. The treatment process consists of a 240 m^3 preconditioning tank, dissolved air flotation clarifier, 240 m^3 preacidification tank and 1,800 m^3 UASB reactor. UASB effluent is recycled back to the DAF for solids removal, to dilute the influent wastewater, and to provide a constant hydraulic loading on the UASB. COD removal efficiencies of up to 90 percent have been achieved.

The biogas production rate is approximately 12,500 m^3 per day, of which 80 percent is methane. A caustic scrubber removes hydrogen sulphide to less than 100 ppm to comply with sulphur dioxide air emissions limitations. The biogas is compressed and piped to production dryers where it comprises approximately 20 percent of total gas usage. A 30 m^3 membrane storage tank provides back pressure on the biogas system and equalized flow to the dryers.

CAVENDISH FARMS

Cavendish Farms in New Annan, PEI processes french fried potatoes. In 1985, they were planning an expansion in production which would have overloaded their existing aerobic activated sludge treatment system. They decided to upgrade their wastewater

treatment facility capacity by the addition of an anaerobic lagoon system to precede the existing activated sludge system.

Operation of the facility began in 1985. The anaerobic lagoon treats 5,700 m^3/day with a BOD of 4,500 mg/L and TSS of 2,000 mg/L. The lagoon reduces the BOD by 93 to 96 percent. The effluent is then polished in the activated sludge system for subsequent direct discharge.

Unique characteristics of the Cavendish Farm anaerobic lagoon is that the system operates with no upstream equalization. The system has been able to effectively tolerate periodic high organic loadings with no deleterious effects on effluent quality. It has also operated with high solids loadings. Only large solids are removed by screening; the remainder of the solids go directly to the lagoon. The lagoon system effectively digests the influent solids thus eliminating the need for an additional upstream solids clarification process.

Energy usage is another advantage of the lagoon system at Cavendish Farms. The gas generated by the lagoon is combusted to generate approximately 850 kW of electricity. Approximately half of the 8,000 to 10,000 m^3 per day of gas combusted is sufficient for powering the entire wastewater treatment system (including the blowers for the activated sludge portion). The excess electricity is exported to the production facility thus saving additional monies for Cavendish. Heat from the electrical generators is used to preheat the wastewater influent to the lagoon.

CASCO

The CASCO facility in Cardinal, Ontario manufactures corn milled products including modified starches. The original treatment system consisted of a facultative lagoon. However, in 1988, the need for improved effluent quality coupled with projected increased loadings from expanded production led to the addition of an anaerobic lagoon for wastewater treatment.

In the current system, the anaerobic lagoon serves as the primary treatment process, removing most of the BOD from the wastewater. The facultative lagoon was converted to an extended aeration activated sludge system for subsequent BOD polishing. The anaerobic lagoon has a capacity of 15,100 m^3 and treats 1,900 to 3,800 m^3 per day of flow. The influent BOD is approximately 3,500 mg/L and the lagoon reduces that by 80 to 85 percent. No equalization/preliminary treatment is required prior to the lagoon.

There are two money and energy saving features of the CASCO system. The 5,000 m^3 per day of gas generated by the lagoon is in the process of being diverted to the production area for use in a feed dryer. Sludge volume has been reduced by digesting waste activated sludge from the extended aeration polishing lagoon in the anaerobic

lagoon. The total sludge generation for the entire system has been reduced to approximately 0.1 kg sludge per kg BOD removed which not only reduces CASCO's sludge disposal costs but also reduces the energy required for sludge handling and treatment.

CONCLUSION

The case studies presented highlight existing facilities that have successfully integrated anaerobic treatment into their wastewater treatment systems. Benefits obtained from anaerobic treatment include:

- Low energy requirements (if biogas is used for steam or electricity generation, anaerobic treatment can produce more energy than it consumes)
- Low sludge production and much lower sludge disposal costs
- Comparable cost and space requirements compared to aerobic treatment processes which have much higher energy and operating costs

Energy benefits from anaerobic treatment can be substantial. Less energy is used in anaerobic processes compared to aerobic treatment since no aeration is needed and mixing requirements are low. In addition, the process converts biodegradable materials to methane gas, producing excess energy which can be used in power boilers, driers, and internal combustion engines. Major gas handling requirements are storage to equalize flow variability, compressors to transport the gas, and moisture traps.

For waste streams with high sulphur concentrations, the presence of elevated levels of hydrogen sulphide in the biogas leads to concern over safety and sulphur dioxide air emissions. However, these concerns can be overcome. There is extensive gas handling experience in the food processing industry and in sludge digesters at municipal wastewater treatment plants.

The number of installations in the food processing industry continues to grow as the operating experience bears out the applicability of anaerobic treatment to a variety of food processing wastewaters.

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